THE DEVELOPMENT AND EVALUATION OF THE KEYBOWL: A STUDY ON AN ERGONOMICALLY DESIGNED ALPHANUMERIC INPUT DEVICE

PETER J. McALINDON
B.B.A., University of Michigan, 1988
M.A.S., Embry-Riddle Aeronautical University, 1989

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy in Engineering
Department of Industrial Engineering
College of Engineering
University of Central Florida
Orlando, Florida

Fall Term
1994

Table of Contents

The Keybowl

List of Tables

List of Figures

Abstract

Although most computers use the QWERTY keyboard as their main alphanumeric input device, several attempts have been made to provide a better, less physically traumatic, interface between computers and their users. Many researchers support the notion of looking into alternate input devices that deliver the same or similar functions of those of a QWERTY keyboard, but with higher efficiency and ease of use. In several cited cases, chord keyboards have demonstrated a high potential to compete with the QWERTY keyboard in these areas. In developing a chord keyboard, design characteristics and the chord coding are the two main factors affecting efficiency.

The emergence of several ergonomically designed keyboards has resulted from an increased awareness and identification of the alleged physical problems associated with the de-facto standard QWERTY keyboard. The new ergonomically designed keyboards, however, have had limited success in alleviating the concern and trauma associated with typing. Few have undergone scientific testing to demonstrate their advantages over the QWERTY design or ergonomic potential. A concerted effort was made to better understand the capabilities of the typist, the keyboard, the typing task, and the way in which they interact. This effort resulted in the design of an alphanumeric input device called the Keybowl.

The Keybowl was designed to provide a solution to the multi-million dollar a year problem of carpal tunnel syndrome (CTS) as it relates to typing. The Keybowl totally eliminates finger movement, minimizes wrist movement, and uses the concept of concurrent independent inputs (i.e., chording) in which two

domes are moved laterally to type. Keybowl users' flexion/extension wrist movements, when compared to QWERTY movements, were reduced by an average of 82.5% whereas movements in the ulnar/radial plane were reduced by an average of 58%. In regard to typing performance, results indicate that users of the Keybowl typed an average of 60% of their regular QWERTY keyboard speed in as little as five hours. Workload measures were significantly higher for the Keybowl group for the first few sessions of testing due to adaptation to the Keybowl method of typing, otherwise they were not significantly different between the two groups. In terms of subjective comfort in using the keyboards, the Keybowl was found to have less wrist and finger fatigue when compared to the QWERTY keyboard. Character error analysis revealed that the eight positions of dome movement were for the most part proportionally balanced. This finding indicates that of the eight positions, no one position was more difficult to actuate than any other.

Acknowledgments

I would like to express my sincere gratitude to my advisor, Gene C. Lee, and committee members John E. Biegel, Kay M. Stanney, N. Clayton Silver, Robert R. Safford, and Chris S. Bauer for their contributions. They provided the personal encouragement, insightful support, and intellectual challenge during my tenure at the University of Central Florida. I also wish to express my deepest thanks to John E. Biegel for his support and high regard for creative problem solving. Because of his support, strong leadership ability, and clever insight, my education has been greatly augmented.

I am indebted to all of the subjects for their invaluable dedication to the project. I am also indebted to my colleagues and friends at the University of Central Florida for their comments and tolerance during this research endeavor. I wish to thank Taha Sidani for his help with software and Keybowl prototype development.

I wish to thank Dr. William March for introducing me to the human factors discipline. His advice, support, and guidance, both as an advisor and friend, has contributed greatly to this research.

My deepest debt of gratitude is owed to my mother and father. I wish to thank them for their undying support, both financially and emotionally. Without their support, patience, and understanding, none of this would have been possible.

Acronym List

CTS	Carpal Tunnel Syndrome
RSI	Repetitive Strain Injury
CTD	Cumulative Trauma Disorder
KRI	Keyboard related injury
VDT	Video Display Terminal
GWPM	Gross Words Per Minute
WPM	Words Per Minute (a.k.a., Net Words Per Minute)
FELH	Flexion and Extension of Left Hand
URLH	Ulnar and Radial of Left Hand
FERH	Flexion and Extension of Right Hand
URRH	Ulnar and Radial of Right Hand

The Development and Evaluation of the Keybowl: A study on an Ergonomically Designed Alphanumeric Input Device

Introduction

With the advent of the information superhighway, computer use is expected to increase dramatically. The vehicles used to navigate this superhighway are not as technologically advanced as the highways they were meant to travel on. These vehicles typically consist of a keyboard and/or mouse. The QWERTY keyboard was developed over a hundred years ago. It gets its name from the spelling of the first six letter keys on the second row of the keyboard (see Figure 1). This keyboard is widely used today and is one of the few visual display terminal (VDT) workstation components that has failed to make the same technological strides as the rest of the workstation components. It is this lack of advancement that has caused the QWERTY keyboard to become suspect in causing repetitive strain injuries (RSIs) such as carpal tunnel syndrome (CTS). Keyboard and mouse operations require unnatural physical positioning of the arms, hands, and fingers; in typical operations elbows are flexed and wrists are ulnarly deviated, pronated, and extended (see Hunting, Grandjean, & Maeda, 1980; Duncan & Ferguson, 1974). Such positions put operators at risk of developing cumulative trauma disorders (CTDs). CTDs are caused by continuous repetitive motions of the hand, wrist, and arm. Muscles, tendons, and nerves are the most vulnerable to such injury (Blair & Bear-Lehman, 1987). In extreme cases, these compromising positions can cause severe wrist trauma such as CTS as well as muscle strains in the shoulders, neck, and arms of the typist.

The speed and processing capabilities of the computer make it possible for a typist to type 8 hours a day non-stop. The long hours spent using the keyboard or mouse coupled with highly repetitive hand and wrist movements appear to be the main culprits in causing CTS (Chapnik & Gross, 1987; Ferguson, 1984; Hall & Morrow, 1988; Kiesler & Finholt, 1988; Stone, 1983). In an attempt to reduce the incidence or occurrence of such trauma, several researchers have addressed issues related to logical key layout (i.e., repositioning of keys for optimal performance), adjustability (i.e., to accommodate different physical requirements), and increasing long-term comfort (see Nakaseko, Grandjean, Hunting & Gierer, 1985). Despite this comprehensive body of research on almost every facet of keyboard design, problems ranging from muscle fatigue to carpal tunnel syndrome are becoming increasingly common in the workplace. In fact, the trauma associated with the QWERTY keyboard is increasing at an alarming, almost exponential rate (see Levine and Black, 1993). It is believed that as many as half of all U.S. workers are at risk of developing CTS. According to the Bureau of Labor Statistics (1989), CTS causes the longest median time out of work for an injury (typically 6 to 8 weeks).

A great concern over repetitive strain injuries has recently been voiced from several clerical and industrial users. Moreover, there has been an increase in the concern over muscle and nerve injuries among secretaries, journalists, and other office workers who use computers or typewriters extensively (Levine & Black, 1993). Hopkins (1990) found that the majority of the reported cases of repetitive strain injury (RSI) came from keyboard operators. Hagberg and Wegman (1987) found a similar trend while quantifying an odds ratio for contracting different cumulative traumas across occupations. The trauma is so wide spread, painful, and costly, that several attempts have been made to redesign the QWERTY keyboard and the environment in which it is used. Several innovative keyboard designs have been, and are currently being, developed because of a recognized need to address these concerns.

Several researchers have identified and attempted to remedy the physically debilitating conditions (repetitive strain injury (RSI) or cumulative trauma disorder (CTD)), associated with using the QWERTY keyboard (Hobday, 1988; Kroemer, 1972, 1989). These attempts have been made primarily through re-designing the keyboard. Many of the newly designed keyboards claim to be ergonomically designed. The term "ergonomically designed keyboard" is commonly used to refer to a number of newly designed keyboards that incorporate human engineering and/or ergonomic principles into their designs. These ergonomically designed keyboards attempt to optimize key layout in an effort to reduce finger travel and fatigue and to promote a more natural hand, wrist, and arm typing posture. Traditional means of keyboard development and design have focused primarily on optimizing physical key characteristics (i.e., size, shape, and tactile response), finger capability (i.e., mobility, strength, and tapping speed), and key arrangement in an effort to increase typing performance. They were designed and developed to remedy a variety of alleged physical problems associated with using the QWERTY keyboard. In addition to incorporating important ergonomic principles into keyboard design, other cognitive and performance considerations have been identified and used. Some designs emphasize user performance and employ various chording key activation schema in order to enhance typing performance (see Noyes, 1983b). In addition to those already mentioned, there have been numerous additional studies completed on almost every aspect of keyboard design and usage. Analysis of key height and weight (Emmons & Hirsch, 1982), how keyboard angles affect performance (Suther & McTyre, 1982), and how keying logics affect human performance (Butterbaugh, 1982) are just a few of the studies that have served as a foundation to the development of the new ergonomically developed keyboards. Despite such a wealth of pertinent information on nearly every aspect of keyboard design, a slight outward rotation of the hand and the reduction of ulnar wrist deviation, which are prevalent in almost every newly designed keyboard, seem to be the only issues being addressed. An equally important, and often overlooked, issue is eliminating or drastically reducing finger movement.

The purpose of this study was to investigate the ergonomic, biomechanical, and typing performances in using a newly designed alphanumeric keyboard called the Keybowl – the first ergonomically designed keyboard that eliminates finger movement and drastically reduces wrist movement while maximizing typing comfort. This study provides an in-depth analysis and evaluation of factors that influence typing performance to better understand the capabilities of the typist, the keyboard, and the manner in which they interact. It investigated how two groups of subjects compared in typing speed and accuracy and how ergonomic performances, in terms of wrist motion, compared on Keybowl and QWERTY keyboards. The Keybowl uses the concept of concurrent independent inputs in which two domes are moved laterally to type alphanumeric characters. This concept of concurrent, or sometimes called simultaneous, inputs is commonly referred to as chording. Chord keyboards have been gaining greater acceptance as potential alternative devices to replace the standard QWERTY keyboard which is now considered the de-facto standard for alphanumeric input. The Keybowl is capable of providing the same functionality as the QWERTY keyboard. This was done by utilizing the chord concept (eight discrete, independent positions on one bowl used in conjunction with eight positions on the other bowl for a total of 64 chorded positions).

In an attempt to ensure user acceptance of a newly designed keyboard, it is important that the new design be flexible to account for individual differences, is easy to learn and use, and offers some health benefit. Training requirements should also be developed to reduce learning time. In support of such requirements, software was developed to aid in learning how to type with the Keybowl. Ease of acquiring and maintaining proficiency also needs to be considered. Finally, the stresses exerted on the fingers, wrist, and shoulders while using the Keybowl need to be evaluated qualitatively and quantitatively. Analyses of these concepts as they pertain to the Keybowl are what provide the main objectives of this study.

Literature Review

Human Performance, Capability, and Measurement

The Guinness Book of World Records has recorded the world typing record at 159 words per minute with only one mistake (Guinness, 1992). Assuming that this was achieved using the QWERTY key layout, numerous performance issues need to be addressed. Is 159 wpm the fastest a human is really capable of typing? Why can't humans type more quickly? Why can't everyone type this quickly? If it isn't a human limitation, can improvements in typing speed be made through better keyboard design? Can improved performances through better key placement be realized? How long could a person type at such a speed? What types of physical or physiological problems would high speed typists encounter in the short or long term? In the long-term? Researchers have been trying to answer these questions for years. All of these questions can be reduced to a single concept: The concept of performance vs. capability. It behooves designers and developers of keyboards to develop a device that enhances performance by adapting to an individual's capability. It is becoming increasingly important to balance a person's capabilities with the levels of demanded performance. Developments for enhancing performance, albeit varied, have focused primarily on increasing words per minute (wpm) measures and have neglected to balance this performance with the capability of the typist. This is especially true for longer-term performance measures and may be a primary contributor to the growing number of RSIs reported each year.

Several researchers have analyzed the time critical aspects of typing performance. Carlson (1963), and Conrad (1965), found that typists' low typing speeds correlate to high error rates. In addition, Howell and Kreidler (1963) found that performance varied as a function of instruction (speed, accuracy, or speed plus accuracy). However, Bergos (1960) found that the opposite actually exists. This finding, however, is dependent upon a speed vs. accuracy trade-off made by the operator. It appears that a general conclusion drawn from these studies is that people tend to set high standards for accuracy as opposed to speed when not given direction as to which to emphasize (Alden, Daniels, & Kanarick, 1972).

Several studies have attempted to pre-screen or determine a person's potential for typing, most with limited success. Flanagan, Fivars, and Tuska (1959) developed a finger-tapping test to screen typing applicants. The test was based on a person's ability to tap with one finger at a time independently of the others and by learning to respond to letters, symbols, etc. with a particular finger. Findings indicated that the tapping test could adequately screen applicants. Such a method is particularly useful where individuals' background and experience are diverse.

A valid, consistent, measure to quantify typing performance is needed to promote future keyboard development and analysis. Inconsistent and invalid measures inhibit promulgation of new ideas or can discredit a well designed keyboard. There are several measurement techniques used to quantify performance in an ergonomically designed keyboard. Two of the most commonly used approaches combine the measurement of speed and accuracy. The first approach utilizes a throughput measure in which an arbitrary correction is made for each error in typing (Alden, et al., 1972). Performance is typically expressed in words per minute or net words per minute (nwpm) after an adjustment of strokes subtracted from errors has been made. The second approach measures speed and accuracy in terms of a bits per second (bps) information metric. This approach is based on more rational grounds for the correction of errors and is typically more difficult to apply (see Alden, et al., 1972)

Acquiring the Typing Skill

Typing skill is perhaps best described as a kinesthetic process. Kinesthetic typewriting becomes habitual when no conscious attention is required to accurately and consistently actuate keys. The majority of early typing instruction methodologies have had kinesthetic typewriting as an ultimate goal (Book, 1908; Blackstone & Smith, 1937). This teaching tradition has continued throughout the years (Cooper, 1983).

In acquiring the typing skill, West (1957) concluded that effective key actuation programs should use only real words and sentences for source material (never random or nonsense combinations). West (1957) also found that early in training emphasis should be placed on speed, lenient error standards should be employed, each student should be allowed to proceed at their own rate, and students should have a complete, unobstructed view of the keyboard. Shaffer and Hardwick (1969) also determined that source material can limit operator performance. They studied the effects of work lengths and word types (real words, nonsense words, and random consonants) on errors and error-detection probabilities. Results showed that proficient typists were able to detect more errors than trainee typists. Being able to view the keyboard maximizes the acquisition of keyboard character location and proper actuation technique (Pollard & Cooper, 1979; West, 1957). Visual deprivation produces a large increase in errors but has no effect on speed (West, 1957). This finding supports the notion that visual feedback is desirable in learning to type, because visual feedback acts as a source of positive and negative feedback (Diehl & Seibel, 1962). It has been suggested that during the initial stages of training, the subject must learn a vocabulary, establish stimulus response relationships, and master the keyboard (Alden, et al., 1972). During the second stage, Alden et al., (1972) suggested that improvement in performance takes place. Typing curricula often include learning in thirteen general stages, they include, but are not limited to:

> location drills, word repetition, warming up drills, upper case, one finger words (training for each of first through fourth fingers), balanced movement, right hand and left hand words, one-hand sentences, double letters, letters, concentration drills, continuity drills, acceleration sentences, and alphabetic sentences (Blackstone & Smith, 1937).

Developing the typing skill is a highly structured, methodical, progressive process. Location drills and one finger words are the first to be taught and are administered to reinforce key locations. They usually start from a home row location followed by letters to be struck by the same fingers (Blackstone & Smith, 1937). Word repetition drills also reinforce character locations using words, a method that rapidly develops kinesthetic response (Cooper, 1983). In addition to word repetition drills, the balanced movement, warm up drills, and right hand left hand words contribute to kinesthetic development as well as learning muscle control for exact sequences of motion necessary to type a character. One hand sentences, double letter, and upper case letter drills are often used to fine tune hand motor skills and sharpen contextual speed of typing. The last group of drills, namely concentration drills, continuity drills, acceleration sentences, and alphabetic sentences are used to complete the kinesthetic development of the typing task. In general, typists are taught to first locate characters on the keyboard, reinforce their location through direct feedback (e.g., seeing a character printed on screen or paper) mechanisms, and continue the process until all character/key locations are memorized. Once all key locations are memorized, proficiency drills to promote the kinesthetic ideal are performed.

The QWERTY Keyboard

In 1866, Sholes and Glidden developed what would several years later become the de-facto alphanumeric input device– the QWERTY keyboard (see Current, 1954, for a complete history of the QWERTY keyboard). Its layout consists of four parallel rows of keys that in sum comprise the 26 letters of the alphabet, 10 numeric keys, and several other specific symbol or function keys (see Figure 1). The QWERTY keyboard gets its name from the spelling of the first six letter keys on the second row of the keyboard.

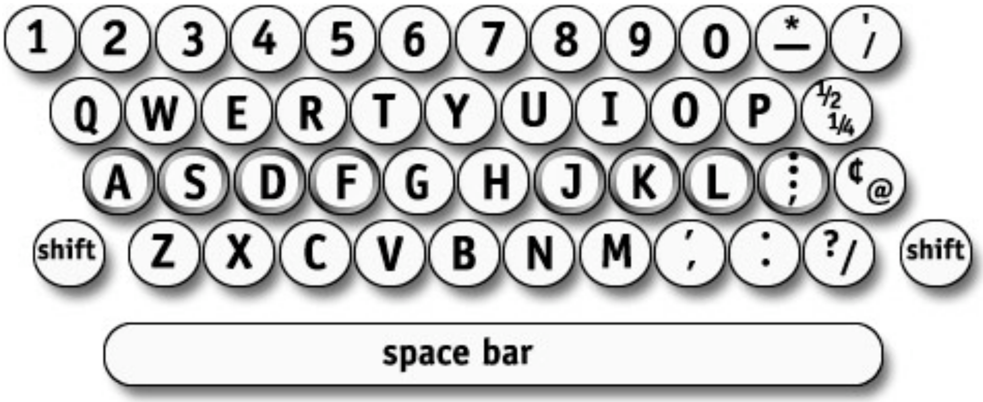


Figure 1. The original QWERTY keyboard character layout (from Current, 1954).

In Sholes' original mechanical typewriter, typing a character was a simple mechanical operation. When a key was pressed (activated), the force applied by the finger caused movement of a metal key bar which had a character engraved on the tip; the engraved character came in contact with an ink ribbon, which in turn pushed the ribbon against the paper resulting in printing a character. A similar process is used when typing with the electric typewriter, however, in an electric typewriter some of the energy needed to move the metal, character engraved, bar is provided by an electrical motor. When keys are activated simultaneously, in either the mechanical or electric typewriters, jamming of key bars often results. The QWERTY layout was developed to alleviate this problem as well as several others. According to Cocking (1970) the QWERTY layout was primarily developed to slow typing so the mechanical hammers would not jam together. In order to slow typing enough to eliminate simultaneous activation of keys, and therefore hammers from jamming, the keys were arranged so that letters that are frequently typed successively (e.g., 'qu') are placed some distance apart on the keyboard. Hence, Sholes and Glidden (1866) constructed a layout that was accommodating to the 'hunt and peck' method of typing and to print words at a speed equivalent to handwriting (Noyes, 1983a).

Several years after its introduction and commercial release, numerous alternative keyboard layouts began to rival the QWERTY key layout in terms of efficiency. It wasn't until the early 1920's, however, that the efficiency and general design of QWERTY were seriously questioned. Researchers and designers began to analyze the logic and placement of letters on the keyboard. Two basic schools of thought on determining the optimum layout of keys were born: Place the most frequently used keys in the center of the keyboard (Dvorak, Merrick, Dealey, & Ford, 1936; Riemer, 1929; Ward, 1936) or assign the least common letters to the center of the keyboard (Banaji, 1920; Gilbert, 1930; Wolcott, 1920). Several measures of keying performance were tested in an attempt to support either school of thought and to discredit the QWERTY design. Prior to 1943, rearranging the letters of a keyboard from the QWERTY layout had been a fruitless pastime due primarily to the wide acceptance of the QWERTY layout. Two important points were brought to light however: First, the amount of hostile feeling that the QWERTY layout has generated, and second, the supremacy of QWERTY retaining its universal position in the keyboard market (Noyes, 1983a). It wasn't until Dvorak (1943) developed his layout that the approaches toward newly designed keyboards became apparent and scientific. Dvorak was the first to make a serious attempt to reject the QWERTY layout. In doing so, he designed a keyboard based on scientific data related to the frequency of use of different letters. Keys were arranged according to their frequency in common English usage. The most commonly used letters were placed on the home row (see Figure 2).

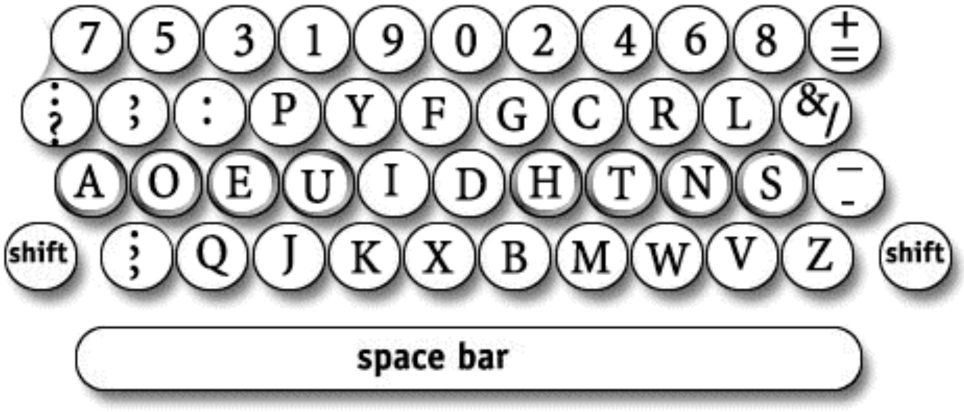


Figure 2: The Dvorak keyboard character layout (from Current, 1954).

Numerous studies have been conducted in an attempt to evaluate the efficacy of the Dvorak layout. Results have been equivocal. For example, Strong (1956) found that on a 1 minute typing test no significant performance differences existed between the QWERTY and Dvorak groups. In support of this finding, Norman and Fisher (1982) concluded that the Dvorak layout increased performance over the QWERTY layout by only 5%. In a 5 minute typing test, however, it was found that the QWERTY group was superior in both speed and accuracy. Based on these findings, Strong (1956) found no justification for adopting the Dvorak layout over the QWERTY layout. Conversely, in a study by McCauley and Parkinson (cited in Alden, et al. 1972), impressive results were found in several programs. Training children and computer programmers are just two of the programs which demonstrated that the Dvorak layout was superior in terms of ease of learning, reducing the likelihood of errors, reducing fatigue, and speed of entry (see Glencross, Bluhm, & Earl, 1989). Unfortunately, methods of the typing procedure, which influence learning, were not disclosed. In a similar finding, Dunn (1971) proposed that the Dvorak layout is superior in terms of ease of learning, reducing errors, and reducing fatigue of data entry.

Dvorak perhaps leveled the harshest criticisms against the QWERTY layout claiming that the following findings made it an inferior layout (Dvorak, 1943):

- For a majority of the population, loads on the left hand (57% of typing) are higher than on the right hand when touch-typing on a QWERTY keyboard.

- The distribution of typing tasks on the rows of keys in the QWERTY keyboard is not balanced. The little fingers are overworked by being assigned to the heaviest keys. The loads on the other fingers are also imbalanced.

- Many frequently used words are typed solely by the left hand; words such as 'was', 'were', and 'are' are all typed with the left hand.

- Thirty two percent of typing is performed on the home row of keys versus 52% on the back row and 16% on the front row. In addition, frequently used sequences such as 'un' and 'br' require excessive row hopping.

In addition to Dvorak's findings, Griffith (1949) addressed the following disadvantages of the QWERTY layout:

- Forty-eight percent of all lateral finger reposition movements are one-handed rather than an easier two-handed motion.

- Sixty-eight percent of typing requires reaches from the home row. A better design can reduce this percentage to 29%.

- The easiest movements for a typist to make are two-handed motions without reaches from the home row (e.g., dkdk).

The QWERTY layout also came under fire for its apparent other numerous disadvantages and physical limitations. Biegel (1934) also described some of the physical limitations of the QWERTY design as follows:

- The ring and little fingers have to be stretched when moving from the home row to the third and fourth rows. This promotes the use of the finger tip which in turn causes the reduction in the stroke strength;

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

- 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.

The Dvorak layout was not the only one devised and tested, however as several other researchers tested various arrangements. Numerous studies, from as early as the 1950s, have compared the QWERTY keyboard to different modified keyboard layouts. Hirsch (1970) found that untrained subjects entered correct data faster on the QWERTY keyboard than on an alphabetically arranged keyboard. In a similar study, Michaels (1971), compared the QWERTY keyboard to an alphabetically arranged keyboard and concluded that the rate of entering correct data was greater for skilled and semi-skilled typists on the QWERTY keyboard, whereas unskilled typists' performance was basically identical on the two keyboards. 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). They determined that the QWERTY keyboard character layout led to a great deal of typing difficulty for novice typists and also suggested that keyboard improvements might be achieved through major changes of the physical key configuration.

The critical analysis of the QWERTY keyboard has continued to the present day; researchers continue to statistically quantify different key layouts based on finger force, range of motion, and physiological concerns (Brunner & Richardson, 1984; Ferguson & Duncan, 1974; Hayes & Halpin, 1978; Kinkead, 1975; Kroemer, 1992; Morita, 1989; Rosinski, Chiesi, & Debons, 1980). It appears that research on the QWERTY keyboard and various other keyboards exists primarily in one of two periods of time. The early works were performed in the 1920s to 1940s. It wasn't until the microcomputer was invented (circa late 1970's) and technology afforded a different type of actuation that research once again resumed.

Despite the many attempts to redesign key layout and statistically quantify the anomalies inherent in the QWERTY keyboard, a few researchers have tried to defend the QWERTY layout features. Kinkead and Gonzalez (1969) 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. These findings, however, are based on the fact that an operator can become skilled in operating any data entry device if given enough time and motivation. They also concluded that an ideal keyboard would ensure that almost all keystrokes alternated between hands. The QWERTY keyboard does this very well. It is therefore Kinkead's and Gonzalez's opinion that the QWERTY keyboard is nearly optimal for speed. Thomas (1972) also suggested that the QWERTY layout helped to speed up the typing operation. Like Kinkead and Gonzalez (1969), his conclusion is based on some of the most frequent digrams which are keyed by alternate hands.

Despite the lively debates and harsh criticisms levied against it, the QWERTY keyboard in use today has become the de-facto standard as an alphanumeric input device. The QWERTY keyboard has dominated the keyboard market since its release over a century ago and is now the standard in the computer market. Most typewriter and computer keyboards in use today follow the original key layout designed by Sholes for his typewriter. Keyboards from computer manufacturers such as IBM (Lexmark), Apple, Microsoft, and other firms are nearly identical to the original QWERTY keyboard.

The major difference between the computer QWERTY keyboard and the original mechanical typewriter QWERTY keyboard is in its operational characteristics. Keys on a computer keyboard are actually electronic switches. The computer keyboard is constantly monitored by the computer to determine which key is activated. Key activation on a computer keyboard is identified by the position of the keys (on or off) and the voltages associated with each. This voltage is converted into a computer recognized format, most often in a standard ASCII format, and is then translated to characters. Characters are then transformed into digitizing images which are displayed on the computer screen (Pollatschek & Gilad, 1984). Additionally, because the computer keyboard is electronically controlled, it is easy to re-program the location of the characters. Software can be used to re-program any key stroke(s) into any character. However, despite this ease of modifying the character layout, there has been a reluctance among computer manufacturers to implement major keyboard modifications. There are several reasons why: (a) the QWERTY's historical precedence, (b) retraining time and expense, and (c) cost to redesign and manufacture. In addition, there has been an apparent reluctance to change to a new breed of better designed keyboards because of the lawsuits that may materialize; companies such as Lexmark, makers of the IBM keyboard, feel that changing the style of the keyboard is admitting that there was, or is, a problem with the old design ("Are CTDs," 1992). Lack of statistical support confirming that the newly designed keyboards are better is another reason why companies are reluctant to change. In analyzing whether or not an operator is willing to learn a new keyboard, Alden et al. (1972) discovered that operator performance measures do not highly correlate to preferences (see Milner, 1988; Monty, Snyder, & Birdwell, 1983). Alden et al. also suggested that typists frequently report that they prefer the machine they are accustomed to using. However, typists change their preference after using a particular machine for some period of time. Preference ratings must therefore be interpreted very cautiously and should seldom, if ever, be the sole basis for design recommendations.

As previously described, there have been several criticisms levied against the design and usage of the QWERTY keyboard. Not only is the QWERTY layout being scrutinized for its alleged inefficiencies, but also concerns over the ergonomic problems accompanying the QWERTY keyboard, including repetitive strain injuries (RSIs), warrant investigation. The controversy and concern is by no means new. Biegel (1934) and Griffith (1949) pointed out that strength of a keystroke by the little and ring fingers is hampered by having to stretch them to the different rows of keys and that tracks from the home row keys are difficult to follow and often cause errors in typing. In order to correct such problems, an abundance of human-computer interaction studies have suggested that newly developed alphanumeric input devices may be more efficient, easier to learn, and may cause less physical trauma than the QWERTY keyboard (Hobday, 1988; Kinkead, 1975; Kroemer, 1972; Nakaseko, Grandjean, Hunting, & Gierer, 1985).

Cumulative Trauma Disorders (CTDs) and the QWERTY Keyboard

There has been an increase in the concern over muscle and nerve injuries among workers who use computers or typewriters extensively. The long-term effects of using a keyboard can cause a number of problems: Repetitive strain injury, muscle fatigue, and decreases in user morale and productivity. The QWERTY keyboard is purportedly a major contributor to a number of typing related conditions that can be physically disabling. These conditions are generally classified as cumulative trauma disorders (CTDs) or more specifically, repetitive strain injuries (RSIs). At a macroscopic level, RSIs are multifactorial disorders that involve mechanical and physiological processes that are directly related to typing intensity and duration. RSIs may develop over a period of weeks, months, or years and may require the same period of weeks, months, or years to recover. RSIs are often poorly localized, nonspecific, episodic, and unreported (Herrin, 1992). These injuries afflict the tendons, muscles, and nerves of the hands, arms, shoulder, neck, and lower back. RSIs are not to be confused with muscle fatigue. Localized muscle fatigue involves mechanical and physiological processes which result in pain and impairs work performance. Muscle fatigue increases with the intensity and duration of work, and recovery occurs with cessation or reduction of work. Recovery should occur within minutes or hours after cessation of work or, in extreme cases, after a night of rest. The symptoms associated with localized muscle fatigue are often confused with those of cumulative trauma disorders (Herrin, 1992). Perhaps the most common RSI associated with the typing task is carpal tunnel syndrome (CTS). A related RSI, tendonitis, is inflammation of the tendon that occurs when the tendon is frequently tensed from overuse or unaccustomed usage of the wrist. It is beyond the scope of this research to discuss any of the RSIs in medical terms. For more in-depth, medically oriented discussion on several of the RSIs refer to Armstrong & Chaffin, 1979; Canon, Bernacki, & Walter, 1981; DeKrom, Knipschild, Kester, & Spaans, 1991; Dunnan & Waylonis, 1991; Durkan, 1991; Goodman, 1992; Hopkins, 1990; Jetzer, 1991; Kroemer, 1989; Moore, 1992; Sauter, Chapman, Knutson, & Anderson, 1987; Skandalakis, Colburn, Skandalakis, McCollam, & Skandalakis, 1992a, 1992b, 1992c; and Szabo, 1992.

CTS gets its name from the structure of the hand that it affects. The carpal tunnel is a bony tunnel located at the base of the hand through which the median nerve passes (see Figure 3). CTS is a debilitating condition that occurs from a compression of the median nerve when its neighboring nine wrist tendons swell. Repeated and forceful wrist movements in the flexion and extension plane cause the finger tendons to rub on the structures forming the carpal tunnel. This constant rubbing causes the tendons to swell (tenosynovitis), which in turn compresses the median nerve. The median nerve then stretches by repeated exertions, and compressed between the walls of the carpal tunnel (U.S.

Department of Health and Human Services, 1989). Direction and magnitude of force are only partial contributors to CTS, however. Speed of movements and incorrect wrist posture also contribute to causes of CTS (U.S. Department of Health and Human Services, 1989). Tingling, numbness, shooting pains, and an inability to grasp objects are just a few of the CTS symptoms. CTS is commonly attributed to work factors. It is not uncommon, however, to attribute CTS to non-occupational factors. Silverstein, Fine, and Armstrong (1986) identified several major factors that contribute to CTS: 1) repetitive movements of the wrists or fingers with loading of the tendons in the carpal tunnel, 2) forceful contraction of the tendons, 3) extreme flexion and/or extension of the wrist, 4) mechanical stress in the hand that puts pressure on the median nerve, 5) vibration, and 6) poorly fitting gloves or pressures at the base of hand or wrist. It has been reported that women are 2 to 10 times more apt to suffer from the disease than men due primarily to the size of the carpal tunnel (Birbeck & Beer, 1975; Barranco & Strelka, 1976). There are several theories as to why CTS has just recently become such a problem. In addition, there are three basic schools of thought as to what causes CTS. Some researchers argue that CTS is not caused by the typing task per se but is more a function of a person's physical, stress, and physiological levels (Arndt, 1987; Lutz & Hansford, 1987; Murphy & Hurrell, 1979). Others argued that CTS has existed for many years (Brogmus & Marko, 1992; Ferguson, 1987). It is just recently, they would argue, that an actual name and classification has been established to appropriately and accurately classify the disorder. And finally, a third group, and perhaps the largest, subscribes to a non-stop, extremely fatiguing, finger movement which is biomechanically inappropriate when typing (Canon, Bernacki, & Walter, 1981; Green, Briggs, & Wrigley, 1991; Kroemer, 1989). They argued that CTS wasn't a major factor until the advent of the computer. Before computers, typists could not type eight hours per day non-stop; they would have to reload paper, reset the manual carriage return, correct mistakes by hand, etc. All of these tasks are believed to offer enough rest to counter the formation of CTS. It wasn't until the computer keyboard was developed that typists could literally type all day. It is believed that this type of activity has caused the growing incidence of CTS (Levine & Black, 1993).

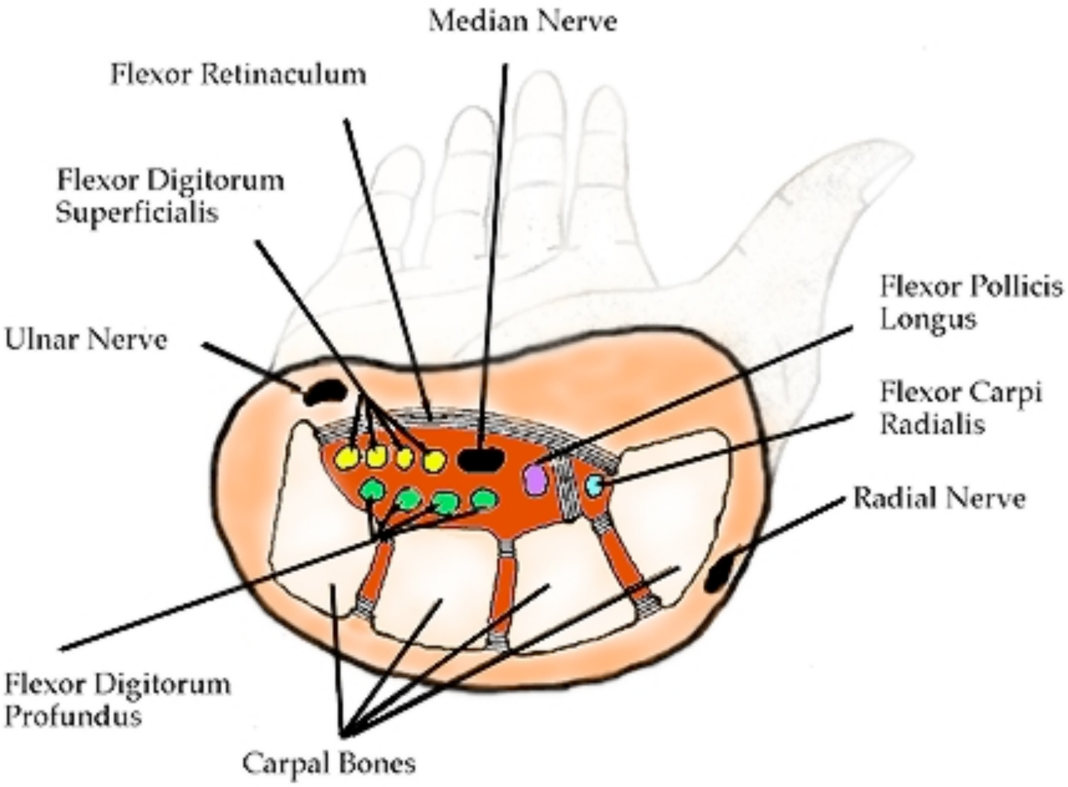


Figure 3. Cross section of the human wrist (from U.S. Department of Health and Human Services, 1989).

Workman's compensation issues have been re-evaluated and hotly debated due to the rapid expansion of claims related to CTS. Liberty Mutual Insurance Company has been tracking CTDs and has been classifying them in an effort to develop an accurate representation of the impact of CTDs on the workforce. The results indicated that in 1991, CTDs made up about 2% of all work related cases reported and about 3.5% of all costs. In 1989, the Bureau of Labor Statistics reported that approximately half of the occupational injuries, over 284,000, were due to CTS. CTS is the second most common surgical procedure in the nation (Levine and Black, 1993). The average cost of a CTD case, according to Liberty Mutual, was about $10,000 in 1991. The National Council on Compensation Insurance, which sets rates, determined the average cost to be about $29,000 in 1991. In total, Aetna Life and Casualty Co. found that RSI related expenses may cost U.S. businesses as much as $20 billion dollars a year. An even higher cost has been estimated by the U.S. Government. The Occupational Safety and Health Administration (OSHA) reported that total CTD related costs could now be running as high as $50 billion per year (Sulit, 1992). It was also shown that the number of claims for CTDs are increasing every year and the top ten states in terms of CTD claims have had a claim rate of 3.2% to 4.76%, accounting for 5.86% to 8.71% of workman's compensation funds (Brogmus & Marko, 1992). It is believed that the increase is due to improved reporting and classification procedures. It may also be attributed to education and early reporting of symptoms that have precipitated cases. Brogmus and Marko (1992) suggested that the cumulative trauma disorders of the upper extremities go largely unreported. Many experts estimated that half of all CTS cases are not reported. In understanding the magnitude of this problem, 250,000 businesses were analyzed to help better describe the extent of the problem (U.S. Department of Labor, 1991). It is believed that the data now available are too ambiguous because of the inaccuracy of reporting from the initial source. The way the data are broken down is also of concern. The statistics are based on two broad areas: Injuries and illness. CTDs may or may not be classified in either of these two categories. The category of classification that includes CTDs of the upper extremities that is of importance is an occupational illness identified as "Disorders Associated With Repeated Trauma."(U.S. Department of Health and Human Services, 1989).

Bartholomew (1992) found that RSI is "fast becoming the leading job-related injury of the 1990's." According to the Department of Labor, RSI injuries accounted for 18% of all job-related injuries in 1982 and then skyrocketed to 55% in 1992. The Center of Health Statistics reveal that CTS affected 1,890,000 million workers, and tendonitis, a related RSI disorder, affects 4,000,000 workers (Bartholomew, 1992). With an average cost of $29,000 per case and with clerical/office employees making up about 7.25% of all reported cases, the total cost for CTS as is relates to typing was estimated to be $29,000 x 1,890,000 x 7.25%= $3,973,725,000.

Much attention has been given to CTDs by the media. It is not uncommon to find statistics that claim CTDs are as high as 48% of all work related problems. Although it could be argued that symptoms associated with CTDs of the upper extremities go unreported or are reported only as group health claims, the same rationale seems to be true for almost any other injury or illness (Brogmus & Marko, 1992). Cases that are reported to insurance companies and likewise to OSHA are really only the tip of the iceberg in terms of the full scope of the problem.

Factors that Influence Keyboard RSIs

Force, repetition, posture, rest, and stress are cited as the major factors in controlling and eliminating keyboard related RSIs (Putz-Anderson, 1988). Analysis of each factor, both independently and in relation to one another, is necessary for designing a keyboard that eliminates or reduces RSIs. Although all factors are equally important in eliminating RSIs, force, repetition, and posture are the key components in the development of an ergonomically designed keyboard. Force and repetition factors relate to the musculature of the fingers and hands that place limitations on their ability to respond in a keyboard task. An important objective of any newly designed keyboard should be to reduce or eliminate fatigue factors and CTS problems associated with force, repetition, and posture.

According to a study by Levine and Black (1993), typing at 60 wpm translates into 18,000 key presses per hour and 25 to 27 tons of force per day. Haaland (1962) verified that the thumb is the most resistant to fatigue and that susceptibility to fatigue decreases progressively from the index finger to the little finger. Dreyfuss, 1959, went on to classify actual finger forces that should be used – forces should range between 4.1 and 11 ounces depending on the finger used. In considering the whole hand as it relates to typing movement, statistics on fatigue and operating force have been lacking. In lieu of these fatigue findings, however, it may be advantageous to correlate key activation force to finger or hand force capability. Research suggests that this type of 'balanced' key to finger fatigue may have the potential to increase typing performance (Harkins, 1965; Pollock & Gildner, 1963). The angle at which the force is applied to activate a key has an affect on fatigue; lateral force results in a more rapid fatigue than downward force (Haaland, 1962). The ring and little fingers have to be stretched when typing characters that are off the home keys. This reduces the strength of the stroke, and leads to the edge of the finger-tip striking the key instead of the center of the tip (Biegel, 1934). Lateral finger forces coupled with higher initial susceptibility to fatigue can adversely affect typing performance. In light of such a finding, only a few of the newly designed keyboards accounted for lateral force fatigue factors. One keyboard that did consider lateral key forces is the TCK keyboard (discussed in next section) which uses ternary keys to type. There is still much to discover in developing variable force keys and the associated performance benefits or detriments caused by them.

Physical Characteristics of the Hand

The most important aspects of any typing activity have traditionally centered around the functionality of the hand. Similarly, understanding the limiting capabilities associated with the hand are paramount in designing an ergonomic keyboard. Several studies related to these capabilities have determined optimal finger tapping rates, fatigue susceptibility ranges, pushing force, and optimal number of keystrokes per unit time (Buchholz, Armstrong, & Goldstein, 1992; Dvorak, Merrick, Dealey, & Ford, 1936; Garrett, 1971; Haaland, 1962, Klemmer & Lockhead, 1962; Haaland, Wingert, & Olson, 1963;).

Dvorak, et al. (1936), found that finger tapping rates decrease from index to little fingers (see Table 1). A slight difference was found in the right hand that was attributed to a higher frequency of use. In a similar study, Fox and Stansfield (1964) collected data on tapping rates with one and two hands. The modal tapping rate for alternate-hand tapping was 0.11 seconds; for same-hand tapping, it was once per 0.13 seconds (see Creamer & Trumbo, 1960; Rempel, Gerson, Armstrong, Foulke, & Martin, 1991).

Table 1

Maximum Tapping Rate (15 sec. test interval) (Dvorak, et al., 1936)

Hand	Left				Right			
Finger	Little	Ring	Middle	Index	Index	Middle	Ring	Little
Tapping Rate	48	57	63	66	77	69	62	56

Haaland, Wingert, and Olson, 1963, examined the effects hand musculature had on the ability of the fingers to respond in a keyboard task. They measured maximum finger pushing force of the adult male hand (see Table 2).

Table 2

<u>Maximum Finger Pushing Force (lb.) (Haaland, et al., 1963)</u>

Finger	Thumb	Index	Middle	Ring	Little
Average	37	24	22	18	12
Range	30-43	17-31	17-26	12-22	6-19

Haaland, et al. (1963) attributed the differences in force to the musculature of the fingers (see Chaffin, 1975). These data highly correlate to the maximum finger tapping rate. In a second study, Haaland (1962) observed that sustained contractions fatigue the thumb and fingers. It is only after practice that these muscles increase their capacity for contraction (Haaland, 1962). This finding is important because actual operator performance may range anywhere from 56,000 to 120,000 keystrokes per day. The angle at which the force is applied also has an affect on fatigue: Lateral forces result in more rapid fatigue than do downward forces (Klemmer & Lockhead, 1962).

Understanding the relationship between the hand, fingers, and keyboard is important in understanding the complete typing task. The finger/hand performance features of the QWERTY keyboard, as defined by Gopher and Koenig (1983) are as follows:

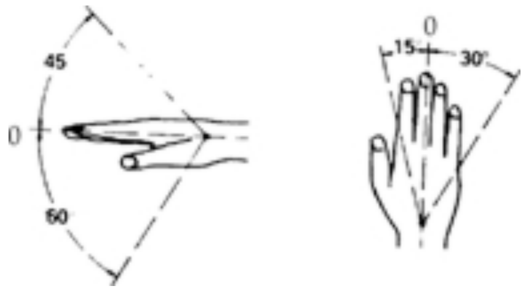
1. Every letter and character is entered by a separate key (although some keys may have more than one function), leading to a large size keyboard with several rows of keys;
2. each finger is responsible for several keys;
3. each hand and finger is responsible for an exclusive set of characters, and
4. typing of most words requires considerable hand and finger travel within the coordinates of the keyboard.

Biomechanical Aspects of the Typing Task

Although much research has focused on typing performance (Ferguson and Duncan, 1974; Hunting et al., 1980; Onishi, Sakai, & Kogi, 1982), it is equally important to consider the physiological limitations and the anatomical requirements of the user given the identified problems associated with the typing task. As previously mentioned, there have been several problems identified with the currently used keyboards. A majority of these problems can be attributed to over use syndromes occurring in the wrist and finger extensor muscle groups. Biomechanical analyses demonstrated that these muscles are subject to substantial sustained static (isometric) muscle contraction during the typing task (Rose, 1991). Keyboard operation is a combination of dynamic and static muscle work. The fingers do mainly dynamic work, whereas the muscles in the forearms do mainly static work (Nakaseko, et al., 1985). In an effort to identify finger force limits, Rose (1991) predicted the minimum keypress force to facilitate relaxation of finger extensor muscles. Postulating that minimum key activation force should accommodate the 95 percentile predicted population relaxed finger weights, his findings revealed that a force of 0.8 newtons was appropriate. The 0.8 N force allows the relaxed fingers to rest on the keys without accidental activation.

Several compromising hand and arm positions have been biomechanically identified as problematic. Hand pronation (palms down), excessive finger extension, wrist deviation, and shoulder abduction are a few of the major problems identified in using a conventional keyboard (see Biegel, 1934; Dvorak, 1943). Each one of these problems is greatly influenced by the others; the degree of hand pronation typically exacerbates the wrist deviation problem. A dynamic analysis is required of the complete upper extremity to gain an understanding of the full breadth of biomechanical implications. The conventional keyboard dictates that the hands be held fully pronated . In the majority of users, this exceeds the anatomical limits of 20 degrees (Rose, 1991). If the elbow is flexed less than the recommended mean of 90 degrees, pronation of the hand becomes even more of a detriment. In order to compensate for this excessive pronation, typists laterally elevate the elbows (abduction of the upper arm). This only relocates the fatigue to the upper arm; abduction in the upper arm generates a troublesome static load in the shoulders (Nakaseko, et al., 1985). The ranges shown in Figure 4 must be considered in providing typing comfort. The greater the deviation from the 0 degree position in either plane, the more detrimental the posture while typing. At the extremes of each movement, physical trauma is most likely to occur.

Comprehensive research concerning lateral force on typing performance has recently begun primarily due to the development of the aforementioned ternary method of typing. Ternary typing differs from binary typing in that ternary keys have three states of character activation instead of two. A ternary key is capable of movement in the fore and aft positions from a middle zero position. The complete ternary concept will be discussed in detail in a later chapter.



(a) (b)

Figure 4. Standard ranges of motion for the hand in the flexion and extension plane (a) and the ulnar and radial plane (b) (Nakaseko, Grandjean, Hunting, & Gierer, 1985).

Keyboard Adjustability

Several developers of ergonomically designed keyboards have decided to keep the QWERTY key layout and instead focus on other ergonomic considerations to increase performance. Some of the most researched ergonomic aspects of new keyboard design are in the areas of opening angle (see Figure 5), chord typing, and physical metrics related to key size. All new designs, in some way, incorporate at least one of these metrics. The basic underlying principle in incorporating one or all of these characteristics is to allow for a more natural, less fatiguing hand and arm position when typing. Supinating the hand and eliminating wrist deviation, for example, provides for a less traumatic means of typing (Scales & Chapanis, 1954).

Scales and Chapanis (1954) studied keyboards with various opening angles. Their findings showed no significant differences in either typing errors or speed as a function of opening angle. Opening angle was varied from 0 to 40°. They did find, however, that half of the operators preferred between 15 and 25 degrees of opening angle. In a similar study, Dreyfuss (1959) found that 11° to 20° is an optimal range based on anthropometric data. Galitz (1965) concluded that a keyboard should permit a opening angle that adjusts between 10 and 35°; he found little performance difference over this range.

In predicting typing performance, key tapping has been applied to various keyboard opening angles. Creamer and Trumbo (1960) tested a range of opening angles on typing performance: 0°, 22°, 44°, 66°, and 88° were examined. They found that subjects had the highest numbers of errors at the 0° opening angle. There was a progressive slight decrease in errors as the opening angle increased. The general conclusion concerning opening angle is that key-pressing performance by experienced typists is stable over a range of keyboard opening angle.

The chord keying design has demonstrated the greatest potential for enhancing typing performance while maximizing ergonomic advantage (cited in Noyes, 1983b). Chording is the process of initiating two or more inputs, usually in the form of key-strokes, to type a single character. The chord method of typing has proven beneficial in many situations where typing needs to be done quickly and accurately. Court reporters and post office clerks were using this chordal technology as early as 1960 (Conrad & Hill, 1968). However, only recently has the chord concept been studied as a potential alternative means of mainstream typing. Numerous studies have been conducted on the chord typing concept (Gopher, 1986; Raij & Gopher, 1987; Wolstein, 1986). Results, albeit mixed, showed that response times in chord keyboards are comparable, and in some instances faster, to response times in QWERTY keying. As Alden, et al., (1972) described it "The basic premise of the (chord) keyboard is that the decision time required to make two simultaneous presses with two hands is small relative to the time required to make a single multiple press with one hand." Fitts (1954) demonstrated that "the difficulty of making small hand movements is a function of the amplitude of the movement and the size of the target. It could therefore be argued that a finger movement which involved merely pressure would be easier to make than one requiring movement in the horizontal plane as well as pressure." (cited in Conrad & Longman, 1965).

Present Day Keyboard Developments

Where do the previously mentioned developments and findings lead us in terms of designing the perfect keyboard? How has all of this previous research impacted or influenced the newly designed keyboards or key layout? Several attempts have been made to optimize key layout in an effort to reduce finger travel and fatigue and promote a more natural hand, wrist, and arm typing posture through design and physical support structures. The result has been an influx of "ergonomically designed" keyboards. These newly designed keyboards incorporate technologies ranging from a foot pedal shift key to chordal keypads that serve two purposes: 1) to reduce cumulative hand and wrist injury (and thereby increase worker productivity) and 2) to reduce health insurance costs. The new keyboards have an improved design through the use of ergonomic principles such as keeping the wrists in line with the forearm, squaring the shoulders, and producing appropriately spaced keys. Several of the newly designed keyboards are fully adjustable to ensure proper position, angle, and comfort for the operator. The wrist is kept in line with the forearm by providing built in wrist rests. In addition to these features, a few of the newly designed keyboards employ various chording key activation schema in order to enhance typing performance.

Of the dozen or so newly designed keyboards, most incorporate one or more of the following design features that enhance or improve typing performance and reduce or eliminate fatigue or injury associated with typing. These design features include:

- splitting the keyboard into two halves to eliminate the shoulder width-keyboard width differential in an attempt to minimize wrist deviations,
- key contouring and flexible key mapping to minimize finger travel,
- built in hand and arm support,
- a ternary capability in which keys rock back and forth to type,
- a capability to rotate and tilt the device into numerous positions, and
- chordal capability in which several keys must be depressed for a single character to be output.

The newly designed keyboards can be broadly classified into 3 categories: a) split, b) radical, or c) chordal. However, the design characteristics are not mutually exclusive. Several keyboards can, for example, be classified into two of the categories listed. Split keyboards are those that separate left and right hand controlled keys into two sections to eliminate ulnar wrist deviation and/or supinate the hand (see Figure 5). Radical designs are those that utilize a non-standard method of key actuation (there are 2 such keyboards). A chord keyboard, a.k.a. multiple key press keyboard, requires several keys to be depressed simultaneously for a single character to be output. For example, the letter "a" can be typed by pressing thumb key a, index finger key b, and middle finger key c. The majority of the discussion will focus on the chordal group of keyboards for two reasons: 1) the chord concept has been more extensively researched than the other two groups; 2) it provides the foundation key activation schema for the Keybowl. A general description of the keyboards that best represent each category are presented to aid in understanding the field of invention at the current time.

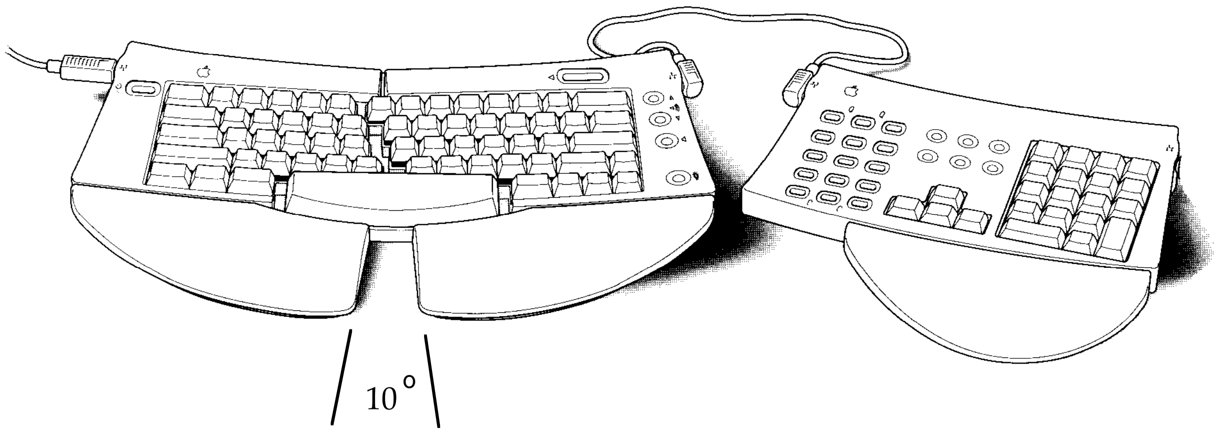


Figure 5. A general design for a split design keyboard for keeping wrists straight (shown with 10° opening angle) (used with permission, Apple Computer Corp.).

Split Keyboards

The split keyboard is the most prevalent of the new designs. Split keyboards make up approximately 80% of the ergonomically designed keyboard market. The commercially available split keyboards include: The Vertical, The

TONY! Ergonomic Key System, the Apple Adjustable (see Figure 5), The Comfort Keyboard System, Kinesis, Maltron, The MIkey, MiniErgo, Microsoft Natural, and the FlexPro. Several of these keyboards have one section of keys for each hand which rotate outward from a hinge centrally located at the back of the keyboard. The two halves are typically configurable through an opening angle range from 0 to 30 degrees to approximate the angle of the arms when the hands are in QWERTY home position. The basic reason for splitting the keyboard is to eliminate ulnar wrist deviation, a suspect position in the development of CTS. A number of these keyboards also allow the sections to be tilted outward to pronate the hand. The TONY! keyboard, in addition to being split, is adjustable to several levels of hand pronation (see Thompson, Thomas, Cone, Daponte, & Markison, 1990). Most layouts resemble the standard 101-key keyboard and all follow the QWERTY layout. Only slight variations exist within the split keyboard group: A thumb operated mouse, key contouring, and optional foot pedals are just a few of the differences between keyboard designs. The keyboard that best represents this group as a whole, and incorporates several of the mentioned features, is the Kinesis keyboard developed by the Kinesis Corporation (see Figure 6). The keyboard's design includes "a sculpted keying surface, separated alphanumeric keypads, thumb keypads, and closely placed function keys". One study, conducted by Jahns, Litewka, Lunde, Farrand, and Hargreaves (1991), indicated that Kinesis muscle loads were substantially less than QWERTY muscles loads on muscles controlling hand deviation, extension, and pronation. In addition, subjects indicated substantial preference for the Kinesis in areas of comfort, fatigue, and usability (Smith & Cronin, 1992).

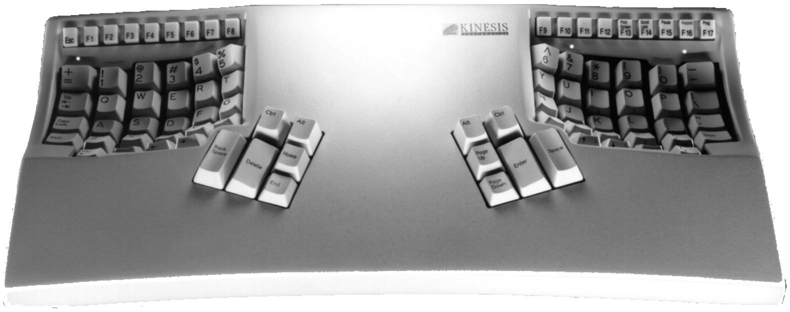


Figure 6. The Kinesis keyboard (used with permission, Kinesis Corp.).

Radical Designs

In the second category of keyboards two radically designed keyboards exist to promote a different kind of ergonomic advantage; they include: The DataHand, which utilizes a "pod" in which each finger has five switches at its disposal: forward, back, left, right, and down, and the Twiddler, which is a hand held keyboard with an integrated mouse that utilizes the chord principle to type (see Friedman, 1992).

As previously mentioned, the Datahand is a keyboard that utilizes finger typing pods for character actuation (see Figure 7). The finger pods consisting of five keys surround the finger tips whereas the rest of the keyboard supports the palm of the hand. Special pods were developed around the thumbs to control space, tab, return, and other special function keys. Also integrated into a pod is a finger mouse. Claims by Industrial Innovations, Inc., maker of the DataHand, include reduction of keystroke repetition by 80 percent and reduction of finger workload by 80 percent. The company also claims that "slow to medium typists usually achieve 100% of their flat keyboard speed within 10 to 15 hours of practice. Within 50 hours, typing speed has increased 30 to 40%." (Kaiser &

Koeneman, 1994). As far as ergonomic issues are concerned, "64% of CTS sufferers using the Datahand reported a reduction of symptoms, with another 24% reporting no increase in their symptoms." (Kaiser & Koeneman, 1994)

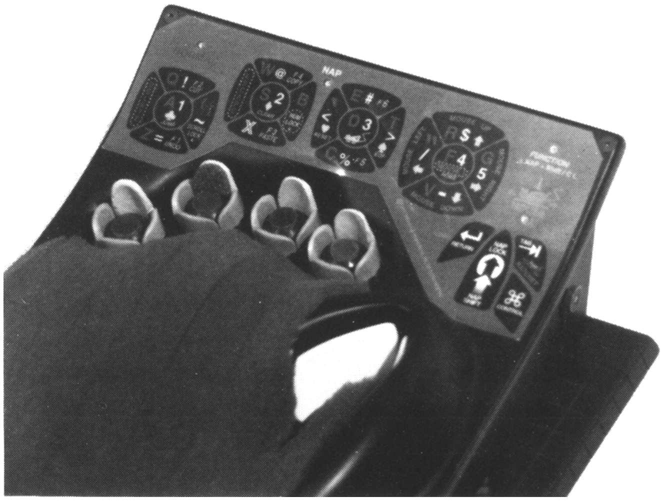


Figure 7. The Datahand keyboard (used with permission, Industrial Innovations, Inc.).

Chord Keyboards

Several keyboards have been developed using the chording principle. Input devices such as MicroWriter, The Bat, and the Ternary Chord Keyboard (TCK) are representative of the different chordal alphanumeric input devices now available. In an attempt to increase typing performance, chordal keyboards have made the most progress. New innovative chordal keyboard designs have been, and are currently being, developed (see Kroemer, 1993b).

Perhaps the most distinctive keyboard to be produced, marketed, and extensively evaluated is the chordal keypad called The Bat, developed by Infogrip (see Figure 8). For information on research similar to The Bat chord keyboard see Gopher et al., 1983, 1984, 1985, and 1986.

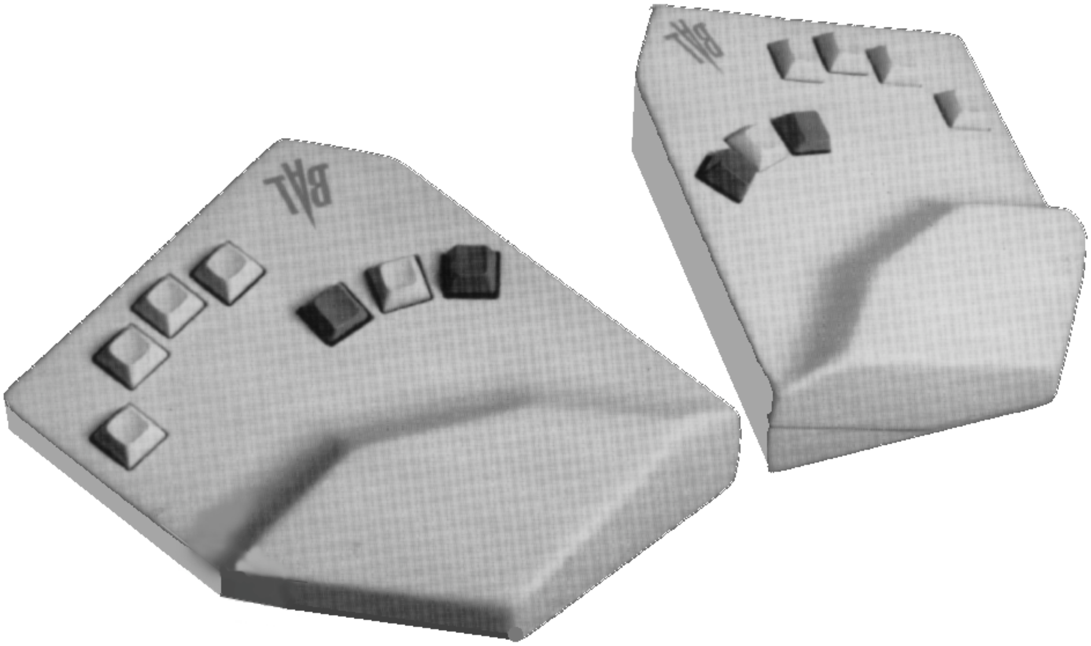


Figure 8. The Bat chordal keyboard (used with permission, Informix).

The Bat keyboard consists of two 7-key keyboards which individually provide 101-keyboard functionality for the left and right hands. The letter "a", for example, is typed by pressing the thumb, index-, middle-, and ring-finger keys. Analyses have been done on this keyboard to determine learning rates, typing speed and accuracy, and user discomfort (Lu & Aghazadeh, 1992). In evaluating its usage, four subjects were used; each had limited QWERTY keyboard experience, were free from wrist injury, and none were proficient in playing an instrument. The experiment was run using one hand and 30 characters, these characters included the 26 letters, comma, period, and two functional commands: space and enter. Subjects were able to memorize all 30 keys in less than two hours. Average learning time per character was 3.58 minutes. After approximately two hours of testing, the subjects averaged 44 characters per minute (approximately 7 words per minute) with a range of 38 characters per minute in the first trial to 49 characters per minute in the last trial. The number of errors ranged from 2 to 13, hence, the average accuracy was 98.3%. It was concluded that the chords on this newly designed keyboard were easy to learn and execute. Further study, however, needs to be done on the keyboard using two hands.

Subjective evaluations were performed to determine discomfort of the neck, shoulders, upper back, lower back, elbows, wrists and hands before, during, and after using the keyboard. Using a 5 point likert scale, subjects rated the subjects rated the keyboard to be comfortable to a little uncomfortable (Lu & Aghazadeh, 1992). The subjects felt only slight discomfort on the wrist caused by the palm rests. For the discomfort rating, it was determined that the adjustment of a hand rest should be provided either toward the keys or in the opposite direction to help users with smaller hands and shorter fingers.

A second well researched chord keyboard that is unique in its own right is the new Ternary Chord Keyboard (TCK) (see Figure 9). The TCK keyboard utilizes eight keys which perform all the functions of a conventional QWERTY keyboard. It is called ternary because each key has three states: pushing a key forward or pulling a key back from its intermediate off position generates two separate on conditions. Operation of the TCK requires motoric skills to "rock the keys" instead of tapping them. Operation of the TCK requires fast and finely controlled force and displacement by the fingertips in a horizontal plane (Kroemer, 1992). A character is generated on the TCK by rocking two or more of its keys simultaneously. This type of keying was developed because it reduces the impact on the fingertips during keying; the effort required for keying is significantly reduced in comparison to conventional keyboards (Kroemer, 1993).

Figure 9. The Accukey a.k.a. Ternary Chord Keyboard (TCK) (used with permission, AccuCorp, Inc.).

In measuring the effectiveness of the keyboard, 22 subjects were asked to use the TCK over a period of two weeks (see Kroemer, 1992). The first week was devoted to learning the operation of the keyboard and the second week to increase the input speed. Each subject worked no more than two hours each workday with the TCK. The subjects memorized and learned to operate the TCK in just over four hours. After 10 hours of use, the average input was 78 characters per minute with an accuracy of 97% with performance still improving.

Further analysis on the new design attempted to determine if finger mobility, digit strength, and tapping frequency played a significant role in keying proficiency. Kroemer (1993b) concluded that there was a low correlation between performance and each of the aforementioned variables. The low correlation between digit performance in tests of mobility, strength, and tapping in relation to performance on the TCK contradict long-held beliefs that keying performance is associated with these metrics. The results of this study, albeit non-comprehensive, demonstrate that the TCK may have greater keying potential than its QWERTY counterpart.

Chord Keyboards

The chord keying concept offers great possibilities in designing a superior keyboard over the QWERTY keyboard in terms of both ergonomics and performance measures. Performance claims of 200-300 words per minute have been made for some chording machines (Noyes, 1983b). The concept of chord keying was first introduced in 1942 by Achille Colombo in his mechanical typewriter and it underlies the Stenowriter stenotype machine (Gallie, 1960). Colombo's original mechanical typewriter required simultaneous activation of one left hand and one right hand key to produce one character (Conrad & Longman, 1965). Training time, on average, takes longer but the additional time needed to become proficient with a chord keyboard is outweighed by the gains in productivity. In support of this claim is research supplied by Ratz and Richie (1961); results showed that speed on a chord keyboard was a function of motor constraints rather than decision time.

Much of the research on chord keyboards conducted in the 1950's and 1960's was targeted toward specific usage. Mail sorting and court stenotypography were the preferred research areas. Conrad (1965) developed and implemented a letter sorting machine that required the simultaneous activation of two keys, one key 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 QWERTY keyboard after 39 weeks of practice (Conrad, 1965). Several other chord keyboards were proposed to be used in mail sorting (see Cornog, Hackman, and Craig, 1963). The combination of chord keying with the method of encoding addresses resulted in starting speeds higher than with manual sorting (Noyes, 1983b). It wasn't until recently that technological advances in the field of computers and electronics prompted many researchers to look into the possibility of a general-purpose chord keyboard to replace the QWERTY keyboard.

Klemmer (1958) tested two subjects on a ten-key chord keyboard. Letters of the English language that are most frequently used were generated by depressing one key while other, less used characters, were generated by depressing two keys. Klemmer concluded that, after ten weeks of training, learning curves were similar to those associated with a QWERTY keyboard. Lockhead and Klemmer (1962) performed a similar study using an eight-key chord keyboard. The keyboard included the 26 letters of the alphabet and a 'word-writing' mode. These 'words' are typed by simultaneous activating all appropriate keys. After several additional experimental studies on their chord keyboard, Lockhead and Klemmer (1962) were optimistic about the principle of chord keying, because for the first time the potential finally existed to breakthrough the typing speed barrier of the QWERTY keyboard.

Owen (1978) designed and developed a one-hand chord keyboard called the "Writehander". The Writehander utilizes five keys: One assigned to the thumb and one assigned to each of the four fingers of the right hand. By using various combinations of the four fingers and the thumb, the Writehander is capable of generating all 128 ASCII code characters. In a similar fashion Rochester, Bequaert, and Sharp (1987) developed a chord keyboard for IBM that utilized the chord keying concept. Keys activated by the thumb, index, middle, and ring fingers made it possible to type characters (also see Lockhead & Klemmer, 1962). This keyboard was the predecessor to many of the chord keyboards commercially available today (e.g., the Bat Keyboard).

General features of chord keyboards as defined by Gopher and Koenig, (1983) and Noyes (1983b) include the following:

- Each finger operates only one key.
- There are only a few keys (usually four or five) to be operated by each hand.
- No hand travel is required and no exertion of large muscles is needed.
- Major skill components are different from those required in standard QWERTY typing. One can acquire and maintain the two typing skills side by side with little interference.
- Letters are identified by a combination of keys, and entries are produced by typing chords. Therefore, both memory and response requirements are different from those in regular typing.
- 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 memory and retrieval requirements of chord input devices are perhaps the main arguments against using them. Seibel (1972) argued that the difficulty and complexity of chord combinations have substantial memory and retrieval requirements. Additionally, he suggested that learning rates, number and type of errors, and response times in operating a chord keyboard are influenced by the assimilation of motor and biomechanical constraints as well as hand coordination problems. Short term memory requirements, however, are an important aspect of any keyboarding task. Conrad (1965) determined that errors in a random letter keyboard layout could be attributed to short-term memory rather than faulty response aiming. Keyboard design evaluations should be related to whether or not the task involves working from memorized codes or encoding directly from an input (Alden et al., 1972). Wolstein (1986) also argued that chord keyboards do not lend themselves well to hunt-and-peck typing, which is an important aspect of typing for novice typists. In providing a lucid chord coding schema and proper operational instructions, Wolstein's argument may not be of major concern of a newly designed chord keyboard. Providing such a schema would allow for rapid identification of characters and in essence provide a hunt-and-peck typing methodology.

Although most chord keyboards have been targeted toward specific tasks of data entry applications, such as mail sorting, the advantages of such a device suggest that a general purpose chord keyboard may be very competitive with the QWERTY keyboard performances. It is becoming apparent that the positive characteristics associated with higher word output and less fatigue may outweigh the negative characteristics of chord keying (Kroemer, 1992a).

Chord Coding: Coding Principles. One of the most important issues in keyboard design is key/character location (Dvorak, 1943; Fathallah, 1988). As indicated from the previous discussion on key layout, character location, which dictates finger assignment in a traditional keyboard, is a difficult task. In determining an optimal layout, motor and perceptual elements and their interaction must be considered. These considerations are often overlooked when designing/developing a chord keyboard. Character location is much more difficult in chord keyboards because of the multiple simultaneous inputs needed to produce a single character. Memory load and some special biomechanical and physical requirements on the user exacerbate this problem. Memorization of the chord combinations and their corresponding character set may not be necessary on a chord keyboard if it utilizes a direct visual reference to chord combinations defined on the keyboard. In most chord keyboards, however, such a visual reference is not utilized.

The application of three coding principles has been proposed to aid in learning chord coding: spatial separation, hand symmetry, and spatial congruence (Fathallah, 1988). These principles should be considered in developing an optimal key layout for a chord device. These principles have been applied successfully on a ten-key chord keyboard (Gopher & Koenig, 1983; Gopher, Karis, & Koenig, 1985, and Gopher, 1986), they include:

> <u>Spatial Separation Principle.</u> This principle has been used by a majority of data entry devices including the QWERTY keyboard. Gopher and Eilam (1979) describe the skill components of the spatial separation principle as follows: Associate each character with a separate key and with a spatial location, facilitate blind positioning of appropriate locations, establish structured key sequencing and five-finger coordination and control, and transform long sequences or verbal symbols to strings of finger operations.

Hand Symmetry Principle. This principle, based on a reference point, suggests symmetrical or mirror image finger(s) use of each hand in producing a character (Fathallah, 1988). It develops character sets for both hands in accordance with the anatomical structure of the finger or hand. It is more closely linked with an emphasis on proprioceptive and muscle information (Gopher et al., 1984).

Spatial Congruence Principle. This principle relies on an external objective reference point (Gopher et al., 1984) and requires the use of congruent finger(s) of each hand to produce a character. As an example, the spatial congruency of the right hand thumb is the little finger of the left hand if the first finger of each hand is considered the first finger from the left.

Chord Coding Analysis. Defining (coding) chord combinations and determining the number of chords needed are essential properties of any chord keyboard design. Developing chord patterns that are mentally, physically, and perceptually easy to master is one of the most challenging aspects of chord keyboard design (Fathallah, 1988; Kroemer, 1993b). In confronting this challenge, a few observations provide important insight: It has been observed that using the most often occurring characters of a language lessens the mental and physical workload on the operator of the device (Gopher, et al., 1984). Appropriate location of these characters affects the speed and error rates of entering data especially over prolonged periods of operation. In addition, location of the most often occurring characters becomes increasingly important as the number of chords increases (Gopher, Koenig, Karis, & Donchin, 1984).

It is important to describe the process of chord typing to understand the problems associated with it. In the chord typing process, characters are defined and assigned to a set of chords. They are then allocated to memory from which they are retrieved in response to a stimulus. Second, a motor response is executed on the keyboard. Raij and Gopher (1987) suggested that motor schemes of the motor response have mainly spatial representational characteristics. The efficiency of the movement is also influenced by physical and biomechanical elements. This led Raij and Gopher (1987) to address three main elements in chord coding: Motor difficulty in performing chord manipulation and activation, relative perceptual difficulty of each chord, and the influence of motor and perceptual determinants on data entry. They developed two separate indexes that assess the influence of motor and perceptual factors in chord keying. Their indexes infer that perceptual and motor factors equally, but independently, affected the efficiency of entering data. They also surmise that the efficiency of finger movement does not depend entirely on physical and biomechanical constraints, but also on the perceptual factors of the chord. A thorough understanding of chord complexity can only be achieved through individual analysis of each chord.

Performance Considerations in Chording. Experimental results obtained by Conrad and Longman (1965) indicated that improvement rates in both the QWERTY and chord keyboards were similar over a 3.5 hour daily, 5 day a week, 7 week training period. Because the training period did not exceed one year, the performance rate was not used as a comparison criterion. A one year period was estimated to result in 'terminal performance' levels. Their study also concluded that the learning period on the chord keyboard took less time than on the standard QWERTY typewriter. This is an important finding for those that need to be taught quickly. Additionally, the chord keyboard was advantageous in situations where operators of data entry devices are hired to be trained.

Two data entry devices, the MicroWriter (described earlier) and the 4x4 keypad, a calculator-like chord device, were evaluated by Wolstein (1986). The main objectives of Wolstein's study were threefold: 1) to determine which device gives the best performance with limited amounts of training and practice, 2) to determine whether the use of mnemonics on the MicroWriter resulted in less errors or whether the absence of mnemonics resulted in confusion among chord patterns, and 3) to determine the time it takes to reach a criterion level of performance on both keyboards. The main findings indicated that certain chord keyboards should not be used unless long training periods are given to their operators. It was also suggested that changes in the coding scheme might affect the outcomes of the results.

In a similar experiment, Raij and Gopher (1986) studied performance measures between a two-handed ten-key chord keyboard and the QWERTY keyboard. Subjects attained input rates of 30-35 words per minute after only 20 hours of practice on the chord keyboard and 20-25 words per minute on the QWERTY keyboard for the same period of time. After 40 hours of practice, some subjects were approaching an entry rate of 60 words per minute on the chord keyboard. Gopher (1986) found that the chord keyboard performance measures were superior to the performance measures of the QWERTY keyboard given that training periods were identical on both keyboards. Error rates on the chord keyboard showed a constant decrease with practice and were generally low. Findings also suggested 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 acquire the chord typing skill with no major interference from one's touch typing skill.

The performance measures found at 20 and 40 hours in Gopher's (1986) study should be quantified statistically in terms of predicting performance. Can performance over a given period, 20 hours for example, give any indication of performance at a higher number of hours? A study performed by McMulkin (1992) examined this issue. McMulkin derived a learning function that describes long term learning on a new keyboard. Several mathematical functions were initially considered to describe keying performances. The most applicable equation investigated was the Log-Log relationship of the form $CPM_i=e^{b_0}T_i^{b_1}$ where CPM_i is the performance in characters per minute on the i^{th} trial (Ti) and b_0 and b_1 are fitted coefficients. Also investigated was the number of performance trials needed to determine the entire learning function. McMulkin varied the value of the Log-Log coefficients and calculated a mean squared error (MSE) for each fit and determined that 50 performance data points were enough to reduce the prediction error to an acceptable level.

Richardson, Telson, Koch, and Chrisler (1987) evaluated keying performances on three different types of keyboards: A one-hand conventional calculator keyboard, a two-hand 10 key serial keyboard, and a two-hand 10 key chord keyboard. Subjects were trained until they reached a predetermined speed and accuracy performance level. After an initial training phase, practice sessions were administered and consisted of encoding five-digit strings. It was discovered that 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 (defined as 875 msec per string, 95 % accuracy) of encoding two-digit strings was about 22 hours on the calculator and the serial keyboard and 97 hours on the chord keyboard. Gopher (1986) suggested that on the 10 key chord keyboard similar performance levels to the one stated by Richardson et al. (1987) can be reached with a shorter training period. This contradiction may be attributed to a few fundamental differences. The design characteristics of the two chord keyboards were different, which in turn affects data entry. Chord coding influences response time on a chord keyboard; inefficient chord coding can result in slower response times. The time and method in which subjects commit the chord patterns to long-term memory can affect the overall time to obtain a certain performance level.

The Keybowl: Introduction

In lieu of the abundance of literature and theory related to keyboard design and use, a comprehensive solution to combat CTS as it relates to typing has yet to be developed. Several of the key components in devising such a solution have been identified and researched but have not been integrated into one keyboard design. For example, chord typing has demonstrated a great potential for speed typing, splitting and tilting the keyboard has demonstrated static ergonomic advantage, teaching with visual feedback (i.e., characters printed on key tops) has proven beneficial for beginning typists and for proficient typists learning a new key layout, and the reduction or elimination of finger and wrist movement is believed to reduce the incidence of CTS. Each aforementioned keyboard design accounts for one or more of these components, but none accounts for them all. The Bat, for example, uses a chordal key actuation schema, splits the keyboard into halves, but fails to provide a lucid character scheme for ease of learning. The Apple Adjustable and Kinesis keyboards offer static ergonomic advantage and characters are easily identified, however research studies indicate that typing speeds in using these keyboards may have difficulty approaching chordal speeds. Most new keyboards attempt to eliminate ulnar wrist deviation, minimize wrist motion in the flexion and extension plane, and minimize finger motion. None, however, eliminate finger motion or wrist motion altogether.

Several of the newly designed keyboards address issues related to static postures of the typing task. In general, the strengths of the newly designed keyboards lie in their ability to reduce or eliminate compromising static postures whereas their weaknesses lie in their inability to minimize dynamic motion. More specifically, the designs minimize static muscle fatigue factors but fail to completely address dynamic muscle fatigue factors (especially in the fingers and wrist).

A new type of alphanumeric input, based on the chording concept and was designed to make typing less physically traumatic, increase typing efficiency, and facilitate typing task learning. The Keybowl was developed specifically to combat the problems of repetitive motion injury as it relates to typing. The Keybowl, as depicted in Figure 10, is an alphanumeric input system which uses a pair of devices, each comprised of an inverted bowl upon which the hands rest. Each bowl is flexibly coupled to a base. The design alleviates many of the problems of key spacing, key size, and key force that are part of every traditional QWERTY type keyboard. The bowl design was chosen because it closely approximates the at rest posture of the hand (also referred to as position of function), which reduces static muscle fatigue and increases long-term comfort. A theorized advantage of this Keybowl concept and design includes less hand, arm, and finger strain and fatigue due to the elimination of finger motion and the relocation of force to much larger muscle groups. It is believed to alleviate repetitive motion strain and injury through its design and flexibility.

The Keybowl is an extremely flexible typing device and was developed to accommodate the user's needs. Different attachments can be used in place of the bowl (e.g., ball or flat board). Other features of the Keybowl include adjustable bowl movement force and displacement, adjustable tilt and height, and complete self containment for use in underwater or hostile environments. In addition, the Keybowl is a perfect candidate for miniaturization and can be used by one or both hands. Lastly, and perhaps most important from a business production standpoint, the Keybowl can be made with fewer parts and more simplified electronics. In terms of manufacturing costs, because fewer parts are needed to build the Keybowl as compared to a regular QWERTY keyboard, Keybowl manufacturing costs are estimated to be approximately 1/10th of QWERTY keyboard costs.

The Keybowl was built to eliminate finger movement, drastically reduce or eliminate wrist motion, and provide a more comfortable static posture for the hand while typing. Wrist deviation is expected to be significantly reduced due to the Keybowl's unique design flexibility in physically moving each bowl in a lateral plane. The reduction or elimination of the finger and wrist repetitive motions provide numerous benefits. In addition to the obvious physical benefits, typists may be able to type for longer periods of time (due to larger muscles doing the work) and more productively. The Keybowl has a built in mouse which allows for complete hands on typing and cursor navigation. The mouse has recently been implicated as contributing to the RSI, CTS problem (see Abernathy & Hodes, 1987; Hill, Gunn, Martin & Schwartz, 1991; Hodes & Akagi, 1986; Jellinek & Card, 1990; Price & Cordova, 1983; Rutledge & Selker, 1990; Trankle & Deutschmann, 1991). Perhaps the most important reason for eliminating finger movement, and finger metrics in general, is that it provides a appropriate means for those with physical handicaps to type. The Keybowl can be utilized by those with finger dismemberment, partial or full hand paralysis, or any other maladies of the hand. In fact, Keybowl users are expected to be the ones that a) have a handicap, b) suffer from CTS, or c) are worried about CTS risk as it relates to typing and are willing to consider a keyboard alternative. It is believed that the majority of Keybowl users will be those that suffer from ailments in using the QWERTY keyboard, and seek an alternative device that either puts them back to work or reduces the trauma of typing.

As a chordal device, the Keybowl typing methodology entails creating a keystroke via a combination of positions of the two bowls. For example, referring to Figure 11, moving the selector bowl to the "hatched" position enables access to the "hatched" concentric circle of the character bowl (here shown to contain the letters I, O, L, M, N, J, H, and U). Moving the selector bowl to the "gray" position would enable the character bowl to access E, R, G, V, C, X, A, and W. Once a position on the selector bowl is selected, the characters on the character bowl can be typed by moving the character bowl into the direction of the character the user wishes to type. The lateral movements of each bowl are the same for all characters (i.e., the character on the outer character rings require the same lateral displacement as those on the inner ones).

Background, Uniqueness, and Detailed Description of the Keybowl

In designing the Keybowl, the functional capabilities of the hand were analyzed. The capabilities are based on physical as well as physiological components of the musculature and dimensions of the hand. Once analyzed, attention was focused on eliminating finger movement. After such analysis, a key and control layout was built up around these capabilities, taking into account the hand's unique form and function, capitalizing on its strengths and designing out its weaknesses, especially in the fingers. The resulting design is hypothesized to be uniquely natural, efficient, and is easy to learn and use.

The proposed design relates to a keyboard for data entry, or more generally the field of data processing. Specifically, it relates to a device wherein the keyboard is ergonomically designed with reference to the architecture of the human hand. That is, no finger motion is required for effective, multiple, differentiated key actuation. The keyboard converts the actuation of its various movements into electrical signals; it is not a part of any one particular machine. However, it can be electrically interfaced to a typewriter, word processor, printer, computer, telephone or other device so that its electrical signals can be utilized to control the operation of such other devices.

Due largely to a proliferation and availability of data entry systems, there has been a dynamic and expansive growth in the use of keyboard devices. Accompanying this expansion are various annoying and debilitating muscular syndromes that result from repetitive, fatiguing hand, wrist, and finger motions that are required in the use of the omnipresent, conventional typewriter-like keyboards. There has been a growing concern in muscle and nerve injuries among clerical workers, journalists, computer programmers, and others who use computers or typewriters extensively. These injuries translate not only into pain and discomfort for the affected users, but also into significant loss of money, time, and productivity.

Force, repetition, posture, rest, and stress are major factors in controlling and eliminating keyboard related injuries (KRIs). Force, repetition, and posture factors relate to the musculature of the fingers and hands that place limitations on their ability to respond in a keyboard task. Analysis of each of these factors, both independently and in relation to one another, is necessary for designing a keyboard that eliminates or reduces KRIs. Although all factors are equally important in eliminating KRIs, force, repetition, and posture are perhaps most important in the development of an ergonomically designed keyboard. A primary objective of the proposed Keybowl is to reduce or eliminate fatigue factors associated with force, repetition, and posture.

An abundance of human-computer interaction literature has suggested that newly developed alphanumeric input devices may be more efficient, easier to learn, and may cause less physical trauma than the conventional typewriter-like keyboards (Hobday, 1988; Kinkead, 1975; Kroemer, 1972; Nakaseko, Grandjean, Hunting, & Gierer, 1985). The emergence of several ergonomically designed keyboards has resulted from an increased awareness and identification of the physical problems associated with the conventional typewriter-like keyboards. This realization has led to numerous developments in the way in which one types. An ergonomically developed keyboard attempts to optimize key layout in an effort to reduce finger travel and fatigue, promote a more natural hand, wrist, and arm typing posture through design and support structures, or employ various key activation schema in order to enhance typing performance.

In reference to eliminating or reducing force and repetition fatigue factors, three very good illustrations are presented by Einbinder (1982), Dolenc (1989), and Gambaro (1993). Einbinder (1982) proposed a typewriter keyboard in which the keys are arranged to conform to the "footprint" of the human hand. This layout of keys is designed with topographically height- and angle-differentiated actuation pads that attempt to minimize overall hand and finger motion. However, the Einbinder (1982) device stresses the importance of having "home positions" for the finger and thumb tips. Therefore, the hands must travel appreciably in order to perform typical typing operations. Thus, the Einbinder device eliminates only a portion of the problems in solving the motion difficulties encountered with conventional keyboards. Stated another way, Einbinder does not substantially eliminate these motion difficulties.

In a similar safety related concern, the Dolenc (1989) design described a one-hand key layout which includes a fan-like array of keys distributed in elongated rows and organized for specific actuation by the thumb and four fingers of the hand. Dolenc's device is concerned with minimizing hand motion, but not finger motion. In fact, Dolenc proposes organizing keys in arrays that take into account the "motion and range of the respective fingers of the hand". Thus, Dolenc clearly considers finger tip actuation of each key. Although Dolenc seriously addresses the issue of minimizing hand motion, his system does not appreciably contribute to minimizing finger motion, and hence related wrist motion. In addition, the Dolenc device does not address the angular and topographical distinctions for individual keys, such as those described by Einbinder. Finally, Dolenc (1989) did not establish a "home position" for the tips of the fingers and thumb as did Einbinder.

Gambaro (1993) proposed an ergonomically developed keyboard which is organized with an array of actuation keys that are disposed generally "to complement the splayed underside architecture of the user's hand". A two-handed implementation is provided wherein each array includes, for each finger in a hand, an associated cluster of input keys that are placed to enable key actuation via only "slight, gestural, relatively closing motion of a portion of a confronting finger, and for the thumb in each hand". In addition, Gambaro tried to overcome the ergonomic problem with a set of keys disposed within two adjustable "hand print" shaped depressions. This device requires no appreciable hand movement of the fingers from the fingertip down to immediately below the first finger joint. Each finger is capable of accessing four keys for the middle, ring, and little fingers, eight keys for the first finger, and a multitude of keys for the thumb. Again, even though drastically reduced, finger movement is still required. Also, all fingers are required for key actuation.

There are eleven other patented designs that address modified keyboard and character arrangements. None, however, appear to address, at least as pointedly as Einbinder, Dolenc, or Gambaro the issues of keyboard use and motion injuries.

Because computing devices are regularly used over relatively long periods of time from grade school to late adulthood, it is becoming increasingly important that a device accommodate the healthy, the physically challenged, as well as the handicapped. The Keybowl permits maximum flexibility in defining character location and physical orientation of the keyboard; it can advantageously be used for the physically challenged individual because it will permit the individual to have the keys located in optimal positions for adaptation to one's unique physical requirement. Because finger movement has been totally eliminated, individuals with partial or full hand maladies can still manipulate the device. The mobility and positioning of the hands and arms will thus have significantly improved hand orientation.

Keybowl dome palm and finger pads are provided to support the hand. Two types of hand rests, both for partial and full hand support, have been identified in the prior art. One kind acts as an actuator and is not intended to support a substantial part of the weight of the hand, but instead imparts some function. Another type of hand rest known in the prior art serves only to space the fingers from the proximity-actuated keys to avoid accidentally operating the keys. The entire hand is supported by the dome. None of the prior art hand rests purport to support the hand while in motion. All have been specifically shaped and contoured to fit the shape of a static hand.

Special key activation is provided for the purpose of selectively altering the location of the cursor. Two sequential downward movements on either of the domes allows that dome to act as a positioning cursor relative to the medium. Because this activation can be performed on either dome, handedness for cursor positioning is accounted for in either left or right hand users. No comparable cursor control system is known in the art. This type of built in mouse activation and control allows for total hand on board typing and mouse control.

The sequential pressing of the dome downward and movement into a colored selection band is used for operating the shift. The shift-lock can be employed by vertically actuating each dome sequentially.

The Keybowl uses a system of chording for input up to 144 user-definable characters. Although chording has been used in some prior art keyboards, the particular scheme of chording used in the present Keybowl is thought to be unique.

Variable dome sizes can accommodate any range of user. Recognizing that a one-size-fits-all approach may not be entirely appropriate to deal with users' hands that are significantly larger or smaller than the median. The structure of the Keybowl proposed permits different dome sizes to accommodate various hand sizes and finger spans.

A variable tension mechanism has also been developed to allow users to adjust the tension of the movement of the dome. Users with larger, heavier hands or larger muscles may prefer to set the dome tension to a higher setting than those with less heavy hands or with smaller muscles. No comparable tension control system is known in the art.

The Keybowls (102 and 104, see Figure 10) are completely sealed and are weather-proof so that they are hostile-environment ready. Their unique design allows for total enclosure, and therefore protection, from water, dirt, dust, etc. No comparable hostile environment, air-tight system is known in the art.

The Keybowl's symmetry and function allows for further reduction in the size of the bowl and other components, thereby making it a perfect candidate for miniaturization. Miniaturization of the keyboard has been a difficult task because of the finger size. The design described allows for easy miniaturization because the finger metrics are not considered as part of the design. In fact, one embodiment requires the use of only one finger, preferably the thumb, of each hand, to operate the keyboard.

The features that characterize the Keybowl, both as to organization and method of operation will be better understood from the following description used in conjunction with the accompanying drawings. These and other objects attained, and advantages offered, by the present Keybowl will become more fully apparent as the description that now follows is read in conjunction with the accompanying drawings.

The preferred embodiment of the Keybowl requires no appreciable hand, wrist, or finger motion. More specifically, input use of the proposed device does not require appreciable shifting of the hand from a rest position, and does not require wrist rotation for maneuvers that are performed by the four fingers and the thumb. The fingers are not required to perform any maneuvering for typing. Rather, instead of focusing on finger-tip activation, the Keybowl is designed to call for only slight motion of a person's arm and/or hand for actuation of "keys."

Description of the Drawings. Figure 10 is a perspective view of the keyboard, constituting a preferred embodiment of the invention, having two domes shaped to fit the natural shape of the hands at rest, with the arms converging toward the keyboard and the wrists straight.

Figure 11 is a top view of the Keybowl character rings with illustrated coded chords.

Figure 12 is a horizontal cross-sectional view of the apparatus depicted in Figure 1, showing the sectors of the keyboard, with Figure 12a illustrating the left-hand side. The right hand side is identical and is therefore not depicted.

Figure 13 is a vertical cross-sectional view of the apparatus depicted in Figure 10, also illustrating generally how a user's right hand is placed in an operative position.

Figure 14 is an illustration of the plan view tilt harness for adjusting the keyboard to various angles.

Figure 15 is an illustration of a vertical cross-sectional view of tilt harness.

Figure 16 illustrates the keyboard situated in the keyboard harness.

Detailed Description of the Preferred Embodiment. In accordance with some of the major underlying concerns to which the design of the described Keybowl is directed, device 10 (Figure 10) takes on a sculptural form which is intended to complement closely the typical palmar at rest architecture of the human hand. Accordingly, device 10 has bilateral symmetry which can be seen in Figure 10, with the left side 102 that conforms to a user's left hand, and with a right side 104 which offers the same setting for a user's right hand.

The illustrated unit 10 is designed such that the keyboard 102 and 104, consists of essentially one half of the keys of the total keyboard. Each section 102 and 104 is secured to a base 28, 29 and cradled in tilting mechanism 192, 194 respectively.

Further describing devices 102 and 104, domes 402 and 404, and character identification rings 222 and 224, which are preferably formed of lightweight molded plastic material, will be supported by a base having generally the shape shown in Figure 11. Referring to the left hand controlled Keybowl, 102, it is the shape of base 28 which defines the structure in which the dome rests and which the electronic components will be housed. Character definition ring 222 will also rest on the top of the base. Eight discrete positions are defined in which the dome is capable of moving 38, 39, 40, 41, 42, 43, 44, 45 (see Figure 12).

The keyboard structure which is provided for the user's right hand in device 10, appearing on the right-hand side of Figure 10, is nearly a mirror image of the left-hand side. Thus, there is provided an array of 8 positions which includes 8 lateral discrete positions 46, 47,48, 49, 50, 51, 52, 53, 54 which correspond to previously mentioned positions 38, 39, 40, 41, 42, 43, 44, 45, respectively.

Mechanical components 87, 81, 23, 24, 73, 21, 91, 92, and 20 coupled with bases 28 and 29, electronics 14 and 15, tilt harnesses 192 and 194, support structures 18 and 80, and domes 102 and 104 collectively make up what is referred to herein as a Keybowl (see Figures 12 and 13). As will be explained, the specific movements which are placed for left-hand and right-hand actuation, respectively, are different.

As previously mentioned, characters are typed using a chordal concept. As an example, movement of the dome on Keybowl 102 into position 38 activates one of eight concentric circles found on Keybowl 104 (see Figure 12). The concentric circles are inscribed and displayed on character ring 224. If the bowl on 104 is now moved into position 46, for example, a single character is output. Keybowl 104 can also be moved into positions 47-54 to type seven more single characters. In this example, all 8 characters on 104 are typed using one input (activation) from 102. The reverse process also holds; a movement of 104 into position 46 allows eight characters to be typed on 102.

Tilt harnesses 192 and 194 are identically constructed with reference unit 10 as shown most clearly in Figures 14a, 14b, and 15, generally include an extendible base structure 30, a hinge 31, and a multi-position, locking, rotatable device comprised of two plates 32 and 99. The extendible base structure 30 can be raised or lowered by moving spring-loaded pin 33 to any of 11 positions (see number 34 in Figure 15) that line the inside of 28 and 29. The keyboard sections 102 and 104 are therefore movable in space to establish optimal positioning for the operator hands. The unique dome shaped hand rest unit coupled with its variable height base allows the operator's hand to project forward in an essentially straight line from the arm and wrist. This is in sharp contrast to the conventional keyboard which requires the hands to be in an offset relationship with respect to the arm in the normal operation of the keyboard. As a result of this new design, there should be a significant reduction in the stress on the wrist and interconnection of the muscular skeletal portions of the wrist, arm, and hands. It is believed that the operator may not only be physically more comfortable, but one can also anticipate improved mental and emotional states of the operator as a result of reducing repetitive motion over long periods of work at computer or other keyboard input devices. It may be found that for certain individuals the keyboard may not be tilted evenly but may have some slight offset with respect to the location of the apex of the domes. The universal pivot unit and multi-position, locking, rotatable device provides maximum optimal location for any keyboard operator. The assembly is releasable, locked in place, and permits subsequent adjustment to compensate for any improper original adjustment as well as complete resetting for other personnel.

Referring to Figure 13, the pivot unit 73 coupled with 93 is a well known assembly that has the sole purpose to activate potentiometers. The potentiometers convert the sway arms movements into an electronically readable format. This allows a computer or other electronic device to sense the actions of 102 and 104. A mounting shaft 21 protrudes through ball 73. The dome attachment assembly unit is attached to the top part of shaft 21 using a threaded shaft 2. The shaft travels freely through ball 23 to allow activation of button 85. Button 85 is used to activate the mouse and is used in typing a capital letter. A spring 87, two circular metal plates 80 and 90, and a threaded lever arm 81 make up the structure for increasing or decreasing the force required to move the domes. The spring is sandwiched between two solid disks 80 and 90 with holes in their centers to allow for shaft movement. The lever arm resides above the upper disk with the lower disk fastened to the top of structure 83. When the lever is rotated clockwise, the spring is compressed resulting in an increase in force required to move the dome. The circular star 136, which has 8 tines in the present design, limits the movement of shaft into one of the 8 tines. The 8 position star can easily be replaced with any star ranging from 1-12 positions to offer character ranges from 1 to 144. It is the position of the shaft within one of the tines that determines the signal sent from unit 104, which when combined with a signal from unit 102, chordally defines a character.

The design described herein also allows for two different types of dome movement. Inserting button 20 locks ball 23 in place. Once locked, the bowl is allowed only to rock on platform 18. A second type of movement, lateral movement, is achieved by removing button 20 and flipping platform 18 over. Ball 23 is now free to move in chamber 24. This allows for lateral, free movement of the dome on the flat side of platform 18.

The embodiment of the Keybowl described herein includes specific character and function assignments. It is possible to modify these if desired without departing from the scope of the present Keybowl. It should also be understood that the present Keybowl is not limited to the illustrated embodiment but that several modifications may be made within the scope of the Keybowl.

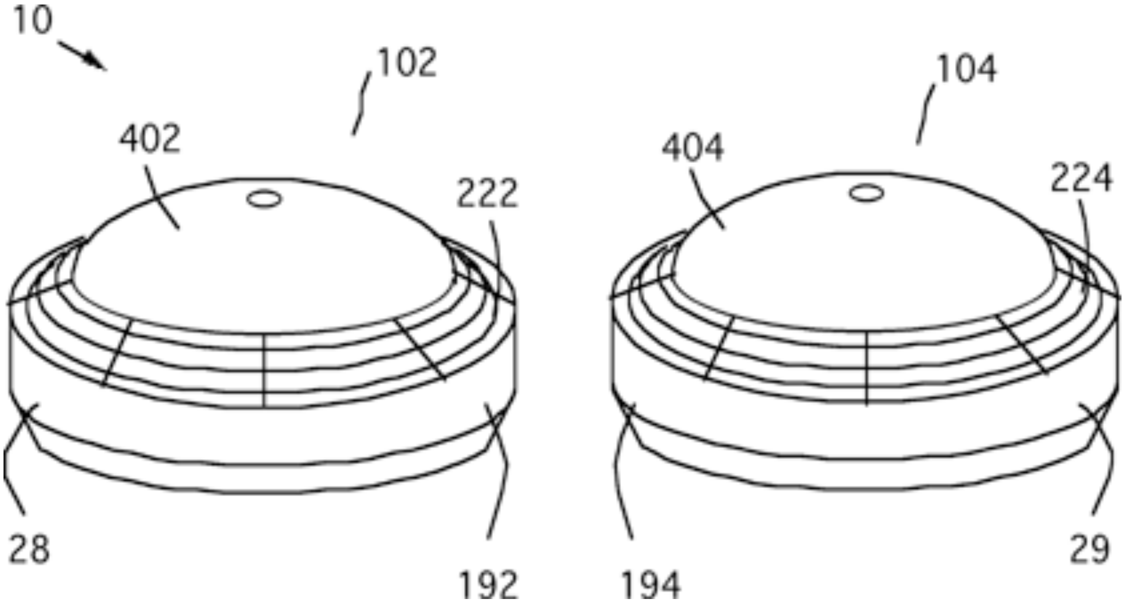
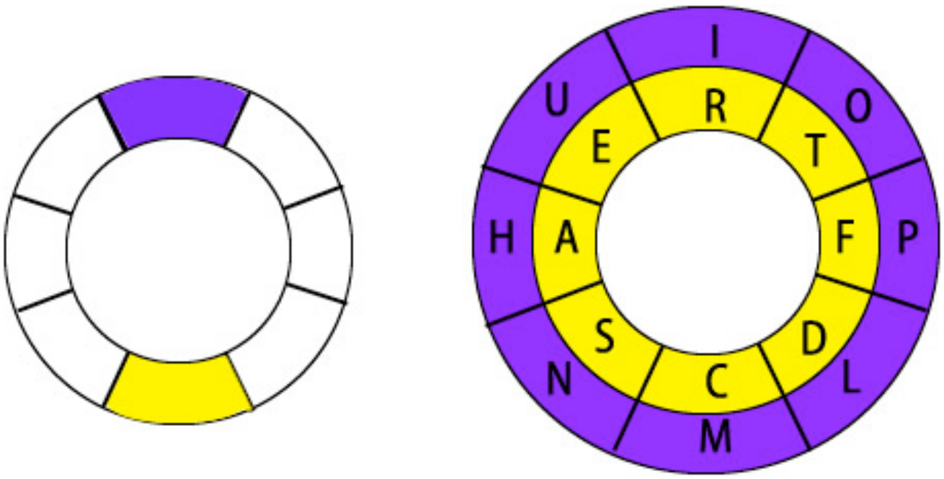


Figure 10. Perspective view of the Keybowl.



(a) (b)

Figure 11. Top view of (a) Selector Keybowl (b) Character Keybowl: An example key chording activation scheme. (Note: six more selector positions on the Selector Keybowl exist and six more concentric circles need to be added to the Character Keybowl to allow for 64 'keys'.)

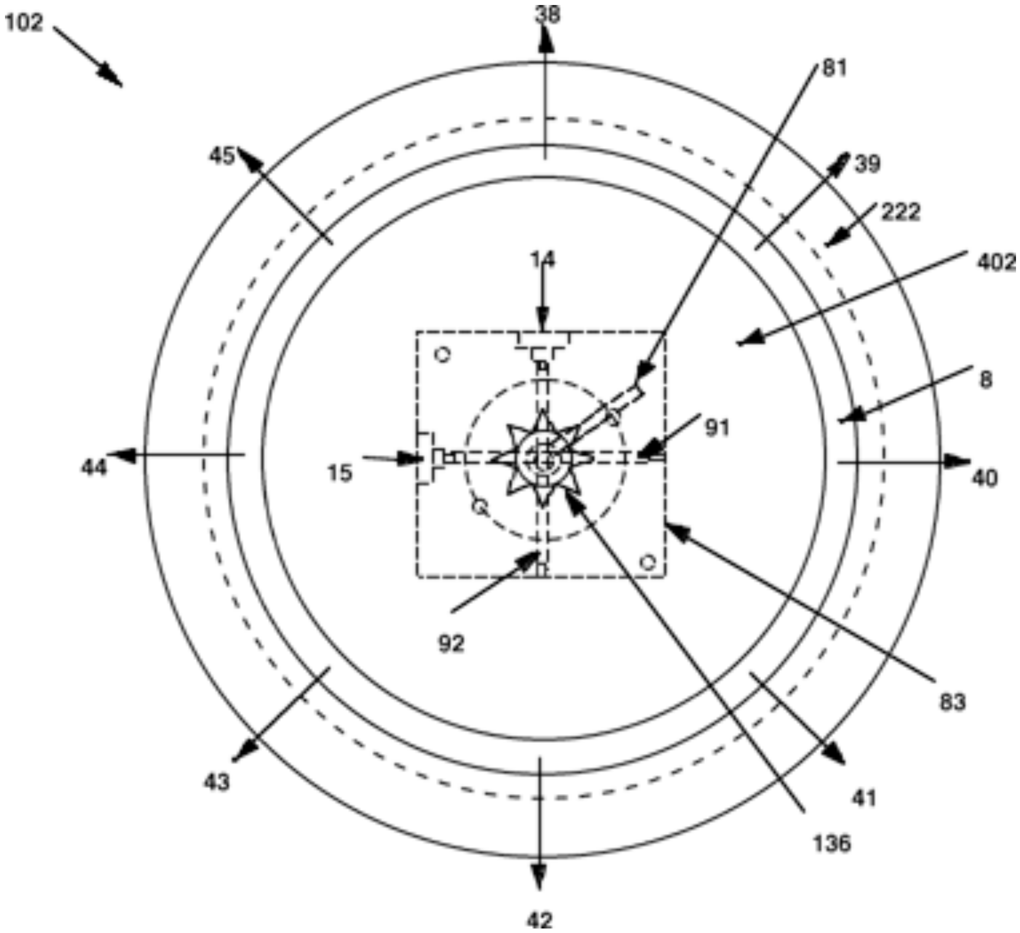


Figure 12. Top view of the Keybowl.

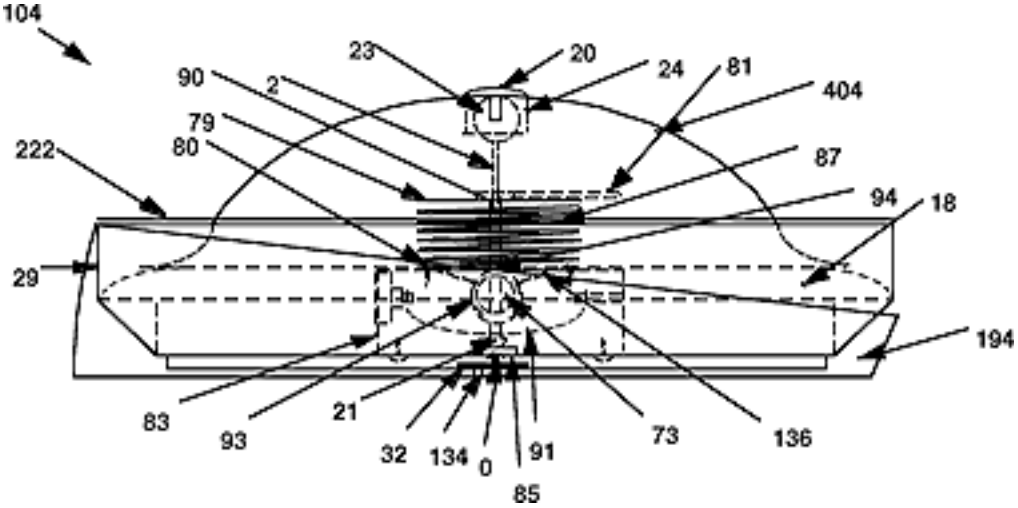


Figure 13. Vertical cross section of the Keybowl.

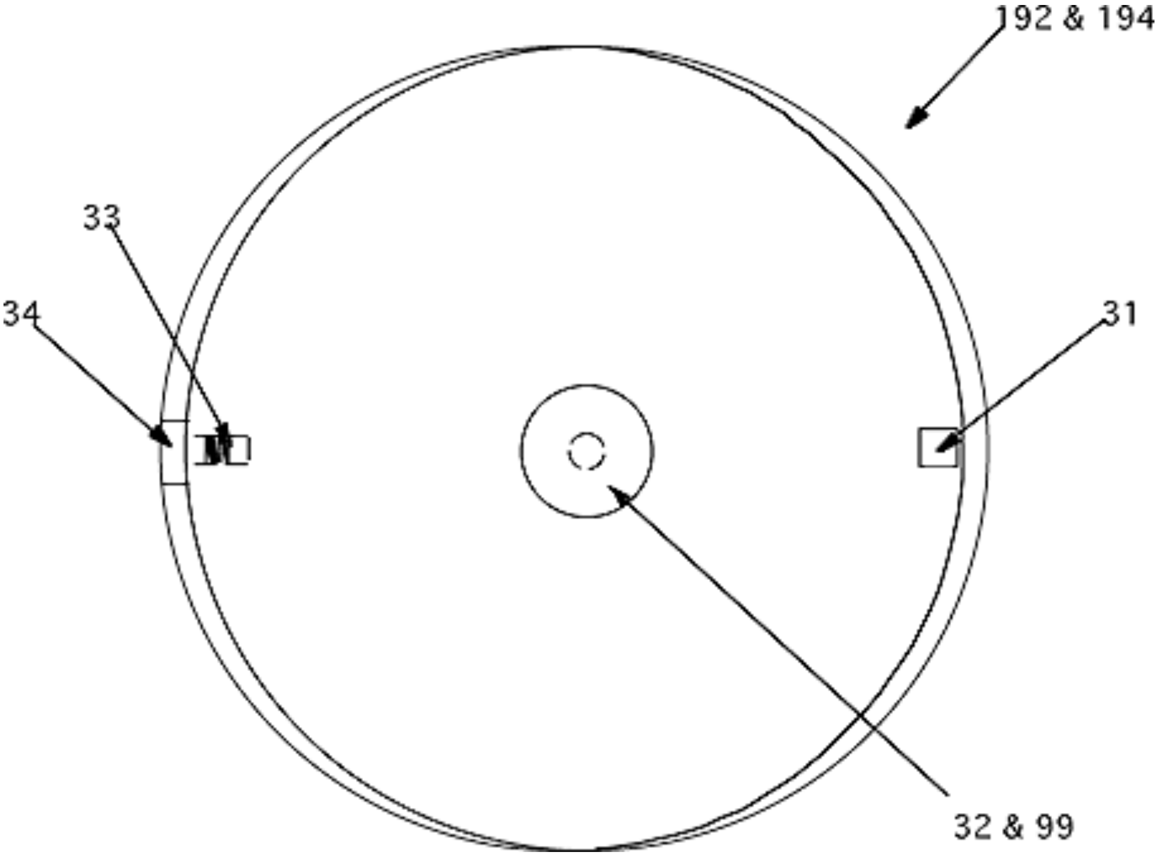


Figure 14. Top view of tilt harness.

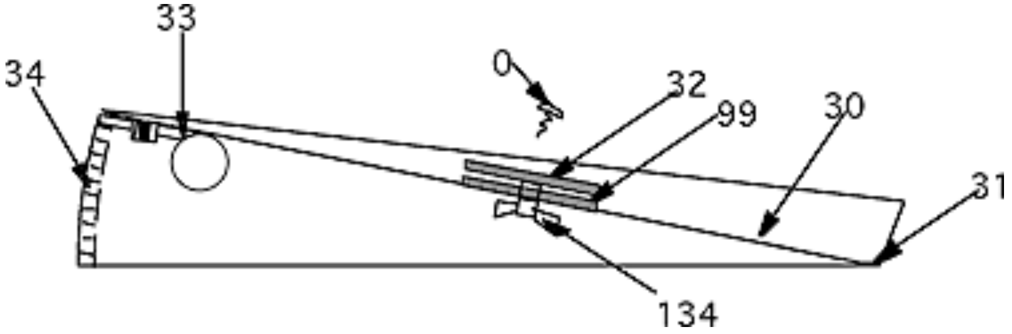


Figure 15. Cross section view of tilt harness.

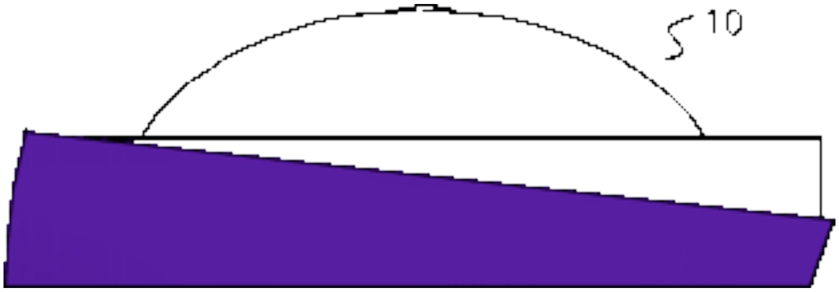


Figure 16. Keybowl situated in tilt harness.

Disparities Between the Keybowl and the QWERTY keyboard

There are several major differences between the standard QWERTY keyboard and the Keybowl (see Table 3). The greatest difference that an experienced typist will have to adjust to is typing without finger movement. Additionally, the movement of the Keybowl into one of 8 positions in a circular arrangement may also cause difficulty initially due to the revamped physical and mental requirements. The physical nature of these two differences may be the major drawbacks as to why an expert's QWERTY mental model may not transfer over so easily to the Keybowl. Does a mental model based on the motions of the fingers transfer in any way to a keyboard that doesn't utilize such motions? An expert typist's mental model is based on kinesthetic finger placement and movement in a particular direction. The Keybowl typing method may have very little transfer from QWERTY expert typists due to a lack of motor movement cues. No agreement has been reached as to whether or not motor components of a task completely change a mental model from a similar task. That is not say, however, that the character mapping cannot be optimized according to the expert typists mental model. Research needs to be done on the cognitive aspects of the skilled typist before such conclusions can be made (see Card & Moran, 1980; Card, Moran, & Newell, 1983; Cooper, 1983).

Table 3.

Comparison of features between the QWERTY Keyboard and the Keybowl

	QWERTY	Keybowl
Finger movement	yes	no
Key activation plane	vertical	horizontal
Method of activation	binary	chordal
Key arrangement	linear	circular
Key identification	visual, printed on key	visual, printed on concentric circle, color coded

Key Actuation

Approximately 95% of alphanumeric keyboards use binary keys as their input mechanism. The keys have two mutually exclusive states: Engaged or disengaged. Binary keys used in conventional keyboards are activated by applying a finger force parallel to the travel of a single key. The chording concept requires activation of more than one binary key simultaneously. The only known keyboard that does not have binary keys is the TCK keyboard. Chord keying in a TCK keyboard is a combination of perpendicular and horizontal forces to key travel. The motor skill requirements of each method of typing are quite different. In touch typing, using a binary key, the control action of each finger is to push down on a single key to output a single character. In the TCK method of typing, keys rock fore and aft to activate characters. In the case of the Keybowl typing method, the motoric requirements are slightly more complex. The two hands have to be moved simultaneously into one of eight directions (see Figure 17).

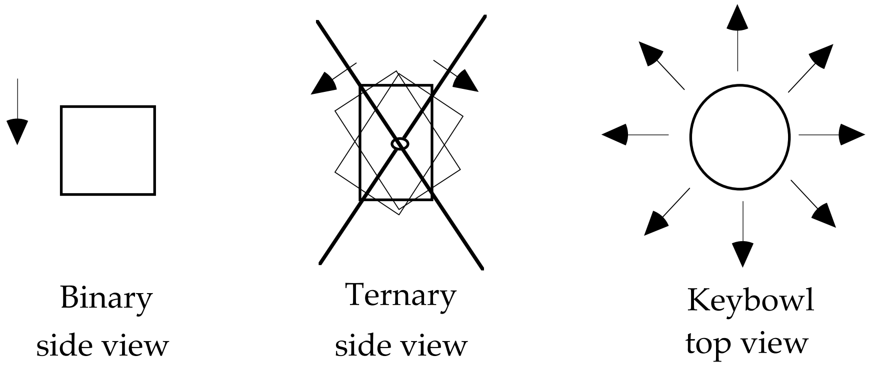


Figure 17. The progression of the different methods of key actuation.

Keybowl hand and arm motor skill requirements are very different to those of the QWERTY keyboard (see Raij & Gopher, 1987; Raikova, 1992). A finger tapping motor skill (QWERTY) versus a lateral hand motion skill (Keybowl) is the essence of the difference in typing with the two keyboards. No applicable research has been uncovered in reference to a lateral hand motion vs. a perpendicular key finger movement with regard to typing speed. One of the goals of this study was to identify and quantify such movements.

The Keybowl requires bowl movement in eight positions covering 360 degrees and therefore an analysis of potential relocation of stresses needs to be examined. In order to classify and quantify some of these potential relocated stress claims, quantitative and qualitative evaluations should be explored in a future study.

In learning to type with any keyboard, a major component of the touch typing skill is based on a memory and retrieval requirement (Card & Moran, 1980; Fathallah, 1988). As previously described, chord devices, in general, require memorization of chord patterns to successfully type characters. The Keybowl, however, utilizes color coded concentric circles to attempt to reduce the memorization requirement and to aid in learning to type. The colored concentric circle schema was devised to act as the Keybowl equivalent to the 'hunt and peck' typing methodology. The colored coded schema allows for rapid identification of chord key combinations. Without the aid of the concentric circles, memory requirements in learning to type with the Keybowl would be expected to be comparable to those requirements in other chording keyboards. Once placement of characters is learned, however, less reliance on the color codes is required. Memorization requirements for the QWERTY layout can be expected to be slightly less than those associated with the Keybowl due to the binary nature of their activation (one key, one required action, one character output). The predominate mental requirement imposed on a novice typist using a QWERTY keyboard is to remember character location or to visually search for characters on the keyboard; the visual search is considered a minor component of the typing task (Card, Moran, & Newell, 1983). The visual task is minor because the QWERTY keyboard, like several other binary keyboards, has each character printed on the top of the key for easy identification. The visual task on the Keybowl is slightly more complex because of the dual identification of color and characters to perform chord typing. The associated memorization components of chord typing to those of binary typing will be analyzed in a future study.

Determining Character Layout

Utilizing what typists already know about typing would substantially reduce the retraining time in learning to use the Keybowl. Proficient typists have a particularly strong and automatized mental model of the typing task. In order to gain a better understanding on how the typing task is cognitively modeled, a GOMS analysis was performed to determine and model implicit and explicit knowledge that users must have in order to type. The GOMS analysis focuses on the basic "how to do it" knowledge and is predictive in terms of two critical factors related to the typing task: Time and errors (Kieras, 1988). The following analysis and discussion was kept to a typist typing in text from a written source. Emphasis was placed an actual typing task, not an editing task.

Norman and Fisher (1982) supported the notion that key layout really doesn't have much of an effect on performance. As such, would a randomly assigned character layout on the Keybowl be any better or worse than one determined by a GOMS or any other type of analysis? The question fundamentally breaks down into whether or not the two devices (i.e., QWERTY keyboard and Keybowl) are similar enough to have equivalent mental mapping schema to perform a typing task. The QWERTY keyboard uses a linear, binary, vertical activation key mapping, whereas the Keybowl has a circular, chordal, lateral activation key mapping. To complicate matters further, the QWERTY keyboard uses the fingers as the primary motor component of the typing task, whereas the Keybowl uses the upper arm or forearm for its motor movement. In terms of mental modeling, the disparity between the two keyboards may be analogous to the two basic types of watches: Analog and digital. Digital watches are read and interpreted much differently as a mental process than are analog watches. The basic components are the same as they are in the keyboards, one has a linear representation, the other a circular. The key question is do these two alphanumeric input devices have enough in common so that the mental model of one can be transferred to the other easily and without a decrement in performance? The actual perceptual and motor mechanisms for typing with each keyboard may be so different that any mental model transfer is not possible. It is the basis of the following analyses to determine whether or not a logical layout can be developed and to determine whether or not prior typing knowledge plays a role in a defining a logical layout for the Keybowl.

A GOMS analysis was performed to construct a mental model of how an expert typist mentally represents the keyboard. It was initially anticipated that the GOMS model and associated analyses for the QWERTY keyboard could be used to determine a suitable layout for the Keybowl. The lack of literature on circular key mapping on any device suggests infancy of such a concept which makes the GOMS analysis more difficult. In addition, the lack of a complete and viable biomechanical model for the hand and wrist (Hallbeck, 1990; Lee, 1991) exacerbate the problem of how well the hand moves in any particular direction which is an important concept for Keybowl layout. Yet, a GOMS analysis was performed on the QWERTY key layout and its associated typing task in an attempt to construct a mental model of how an expert types. Using this model in conjunction with its associated task analysis, a suitable Keybowl "key" layout for those already proficient in typing with a QWERTY keyboard was devised.

Construction of the GOMS model occurs in four phases; each phase is represented by a letter in the GOMS acronym. The first letter, G, describes the goals that are sought in the typing task. Kieras (1988) described a goal as something a user tries to accomplish. In attaining a goal, a user is often required to accomplish multiple subgoals. Each goal or subgoal is defined as an action-object pair <verb noun>. An example of a goal related to the typing task is <enter alphanumeric>. As the goal relates to the typing task, the user is trying to accomplish a mental and motor task of successively inputting keyboard characters into an electronic or manual device while at the same time maintaining a high level of accuracy and keying speed. Expert typists rarely need to think about what they are typing and can often times perform parallel processing while typing (conversing for example). It is in achieving this type of mental model goal, one that is second nature, that is of interest.

The next letter in the GOMS acronym, O, refers to operators or actions executed by the user to perform a typing task. Similar to the goal, an operator for the typing task also uses an verb-noun pair. An operator related to the typing task would be defined as: <press key>. There are two basic classifications of operators: External operators and mental operators. External operators are further broken down into perceptual operators such as reading text to be input, and motor operators such as pressing a key. The observable factors or external operators related to the typing task include textual stimulus from two basic sources: Hard copy text and computer screen text. Factors that influence readability of the text includes such things as font size, font type, text legibility, and color contrasts. These factors greatly influence typing performance and may impinge on the mental model. The second classification of operators, the mental operators, are much more abstruse in nature; they are non-observed and must therefore be inferred by the experimenter. Examples include actions such as simple decision making, storage and retrieval of information to and from working memory and/or long-term memory, and modeling a goal to be accomplished. Memory and storage retrieval of information provides the basis for understanding and constructing a mental model of how expert typists represent a keyboard layout. The following operators were defined to reflect the distinction between long-term and working memory as they are typically used in a typing task operation (Kieras, 1988).

Recall that <working memory-object-description>
Retain that <working memory-object-description>

Forget that <working memory-object-description>
Retrieve-long-term memory that <long-term memory-object-description>

According to Kieras (1988), recall means to fetch from working memory; retain means to store in working memory, and forget means that the information is dropped from working memory because it is no longer needed. Additionally, because the typing tasks involving long-term learning and forgetting are not pertinent, retrieve-long-term memory has been introduced.

Primitive operators are the lowest level operators. Primitive motor and perceptual operators are based on the most basic actions needed for analysis of the typing task. For the typing task, such primitive operators include:

Home- hands to home row keys
Press-key <key-letter>
Type-in <string of characters>, or in the case of an error
move cursor to <x,y> or Press-key <backspace>

The third letter in the GOMS model, M, refers to the method or sequence of steps used to reach a goal. Steps may consist of one or more external operators or a set of mental operators involved with setting up and accomplishing a subgoal (Kieras, 1988).

And lastly, the letter S refers to the selection rules. The intent of a selection rule is to administer control of the appropriate method for accomplishing a goal. Sets of selection rules consist of several If-Then rules (e.g., IF the letter "a" is read and is to be keyed in THEN press key "a". This would be followed by accomplishing the goal of <inputting "a" correctly>). Each condition consists of one or more operators that test working memory, test contents of task description, or test external perceptual situation (Kieras, 1988). They can not, however, be motor operators (e.g., press key).

Representing a Mental Model of an Expert Typist Using GOMS

In building a mental model using the GOMS analysis it becomes necessary to assess that natural steps occur in a user's typing method. Typing methods often differ greatly from expert to expert, therefore a consolidation of mental models is needed. The consolidation can be done in a variety of different ways: Account for all the behaviors in the GOMS model or develop a quantitative approach to assess each mental model representation. Both were investigated.

Accounting for all of the typing behaviors is made easier by making several judgment calls. Several speculative, hypothetical claims and assumptions about how expert typists think about the typing task need to be made. The purpose of making such judgment calls is to actually model how typists perform the typing task. Once these assumptions are made, however, the methods are determined by the design of the system and no longer by judgment. To simplify things further, complex processes such as reading the characters will be replaced by operators representing the complex process. A "yellow pad" heuristic is utilized to put the results of a complex mental process into a task description (Kieras, 1988). Once set-up, a simple operator accesses this result when it is needed.

Developing a quantitative approach to consolidate the mental models of experts for developing an optimal keyboard layout consists of evaluating and adequately modeling the human processor. Several human characteristics such as visual image storage, auditory storage, which are part of working memory, work together with perceptual processing, cognitive processing, and motor processing to provide the basis for the quantitative approach in analyzing typing performance. Each individual mental model must first be quantified to consolidate the mental models. Several principles of operation have been developed for such an analysis. Of the nine described by Card, Moran, and Newell (1983), the principles related to Fitt's Law, Power Law of Practice, Uncertainty Principle, and the Variable Cognitive Processor Rate Principle are perhaps most applicable to the typing task. The well known Fitt's law relates to the time it takes to move the hand to a target of a given size which lies a given distance away (Card, Moran, & Newell, 1983).

$$T_{pos} = I_M \log_2(D / S + 0.5)$$

where I_M=100 [70~120] msec/bit, D= Distance, S= Size of Target

The other principles used in conjunction with Fitt's Law provide the basis for what is known as the Keystroke-Level Model (Card, Moran, & Newell, 1983). This Keystroke model is useful where it is possible to specify the user's interaction sequence in detail. For the purposes of the Keystroke model, it is only necessary to account for the top-level structure of the unit task (Card, Moran, & Newell, 1983). The Keystroke model is an important part of the quantitative evaluation of multiple mental models. This is primarily due to the execution of a unit task defined in terms of four physical-motor operators. Only two, however, are considered for the typing task: K (key stroking) and H (homing). The total times for each component are computed and summed to derive a total time of execution. For example, the total time T_k spent in key stroking is the number of keystrokes n_k times per keystroke t_k, or T,=$n_k t_k$. When an expert QWERTY typist operates a Keybowl, the hand movement, including the fine positioning adjustments of the hand on the Keybowl, is represented by a H (home) operator. Card, Moran, and Newell (1983) assigned a constant t_H of .4 sec for movements between any two devices. The values of K and H can then be substituted in various methods in the GOMS analysis to determine optimal character layout. The Keybowl may have a reduced H value due to having to home only your hands on one point as opposed to having to home 8 fingers and a thumb on a QWERTY keyboard.

Another approach that has just recently been introduced is the simulated annealing approach used to optimize key location (Light & Anderson, 1993). The annealing process utilizes combinatorial optimization of a mathematical function to produce an optimal layout. Characters are swapped two at a time until a mathematical function is minimized. Minimization achieves optimality as far as the presented algorithm is concerned.

A third approach that can be utilized takes into account the natural reflex of an expert typist. Assuming that keystrokes are subconsciously performed, expert typists using the Keybowl may be inclined to make consistent movements in the same direction in which they type on a QWERTY keyboard. Experts could be presented with a randomly generated character. As soon as the character appears on the screen, a software counter would start (msec can be used). The user would then move the bowls in a position that best maps the mental map they already have for that particular letter. Once a movement is made, the total time from character presentation to movement would be computed. Based on these times and movements, an adequate character mapping can be developed based on the QWERTY mental model. Once a key layout has been developed, aspects of cognition (short term memory, etc. (see Card, et al., 1983)) associated with the typing task can be analyzed. Therefore, depending on what types of processes and times are gathered, an optimal layout can be devised.

Construction of a Mental Model Using GOMS

As previously discussed, understanding the typists goal(s) are paramount to successful GOMS analysis. The typist's goal(s) can be determined by considering the actual and intended use of the keyboard; the methods are determined by what actual steps have to be carried out. Predictions can then be made for learning and performance characteristics and can also be used to help correct and revise the design. Also important are the types of perceptual inputs that go into building a mental model for typing. Visual, auditory, and tactile (process of key sequencing) perceptions are imperative in performing the typing task (see Rumelhart & Norman, 1982). The mental model is developed through an advanced understanding of matching a visual stimuli to a highly developed tactile response. A character that is visually perceived, or a word that is either heard or thought of, is represented in working memory. Once in working memory actions necessary for entering that character can be performed. Actions include both motor and mental components. A mental response is initiated when a character held in working memory is matched to a location on a keyboard. A motor response is then initiated to activate the key. The way the keys are arranged both alphanumerically and physically play an extremely important role in how a mental model is formed. A proficient typist not only knows when a character is input correctly, but also knows how the fingers on each of the hands are moving to actuate a character. At an expert typing level, any deviation from this internalized feeling triggers a wrong character mental response. Many typists know exactly when an error occurs and correct for it without ever seeing, or in some cases consciously perceiving, the error. The GOMS analysis focuses on the tasks of such a proficient typist.

Construction of the GOMS model begins with defining a hierarchy in which the most general typists goal is on top with the primitive operators at the bottom. The model is also performed at a breadth resolution first criteria (as opposed to depth first). That is to say that all goals at each level must be obtained before proceeding downward on the hierarchy. Accomplishment of the top level goal is defined by the terms of high-level operators. Next, methods are described for performing high level operators in terms of lower-level operators. The analysis is complete when the operators are at their lowest level (primitives). In evaluating the hierarchy, the breadth analysis helps identify how methods compare at any particular level and how they are similar to one another. In addition, breadth analysis ultimately aids in capturing consistency in the design.

The following steps have been abstracted and modified from the method described by Kieras (1988) to appropriately construct a typing task mental model using the GOMS analysis.

Step I: Choose a top level goal and method for an expert typist. The top level task has a unit-task control structure in which the user accomplishes the overall tasks by performing a series of smaller tasks. Based on the previous discussion of goals and methods, the typing task goal would be to key in alphanumeric data accurately and efficiently (disseminate, manipulate and/or reproduce textual or auditory information). The method would include, generally, the following steps:

Step a: Get next unit task information from text or verbally.

Step b: Decide: if no more unit tasks, then report goal finished.

Step c: Accomplish the goal of performing the unit task.

Step d: repeat as necessary.

Step II: List the series of steps an expert typist performs. The description is kept at a high level. Definition of high-level operators and the bypassing of complex psychological processes are performed in this step.

Step III: Verification and validation of methods are performed. Assumptions about user's expertise with regard to the number of operators in a step are checked for consistency. Method details are worked out and verified.

Step IV: Perform criteria analysis to make sure that all operators at a particular level are met. Once all operators are at their primitive level, continue to the next level. However, if the methods do not generate the correct action sequence, corrections need to made.

Step V: Re-evaluate judgment calls and assumptions. At this stage sensitivity analysis can be performed to capture the effects of different assumptions and judgment calls. Judgment calls and assumptions can be used to systematically evaluate whether they have important impacts on the key design and/or layout.

Defining Methods and Selection Rules Associated with a Expert Typing Task

The uppermost goal of the expert's typing task is matching what the typist sees to that on a VDT. Or generally, the task is to disseminate, manipulate and/or reproduce textual information. Reproduction is usually done in some form of printed or electronic manner. The GOMS analysis employed starts with a unit-task method and a selection rule that administers control to the appropriate method.

Method to accomplish goal:
Step 1: Get next unit task information from text or other input source.
Step 2: Decide if unit task is complete
Step 3: Repeat as necessary until entire document has been input.
Selection rule set for the goal of performing the unit task
IF the task is reading the letter "a" and it is to be keyed in THEN accomplish the goal of pressing key "a".
IF the task is correcting a mistake THEN accomplish the goal of deleting text
Report goal accomplished.

Method to accomplish goal of inputting alphanumeric character (QWERTY keyboard):
Step 1: Identify the character or words to be typed
Step 2: Determine the first letter to be struck
Step 3: Determine the location of the character on the keyboard
Step 4: Determine which finger is to be used
Step 5: Determine the direction and length of necessary movement
Step 6: Initiate movement
Step 7: Report goal accomplished

Method to accomplish goal of inputting alphanumeric character (Keybowl):
Step 1: Identify the character or words to be typed

Step 2: Determine the first letter to be struck

Step 3: Issue chordal key activation routine (2 simultaneous or 2 sequential inputs)

Step 4: Determine which hand(s) is to be used

Step 5: Determine the direction of necessary movement

Step 6: Initiate movement

Step 7: Report goal accomplished

Method to accomplish goal activating a key on a QWERTY keyboard (generic method using the formal variable approach)

Step 1: Recall the location of a character on the keyboard. Retrieve from long-term memory that the key is in location x and is controlled by finger y with finger movement z.

Step 2: Recall that key name is x, and move finger to y on keyboard

Step 3: Press key down

Step 4: Recall that key name is x, and verify that x was activated.

Step 5: Release key x

Step 6: Forget key name and report goal accomplished.

Method to accomplish goal activating a key on the Keybowl (generic method using the formal variable approach)

Step 1: Recall the location of a character selector zone. Retrieve from long-term memory that the key is in location x and is controlled by hand y with movement z.

Step 2: Recall the location of a character on the character Keybowl. Retrieve from long-term memory that the key is in location x and is controlled by hand y and movement z.

Step 3: Recall that key name is j, and move hand x to position y on k and move hand l to position m on Keybowl n

Step 4: Recall that key name is x, and verify that x was activated.

Step 5: Release bowls k and n

Step 6: Forget key name and report goal accomplished.

Character location based on the times, computed by either the Keystroke model or by simulated annealing, can be optimized on either the linear key layout (as on the QWERTY) or the circular key layout (as on the Keybowl). The GOMS analysis helps identify the primitives of the keying task which are needed for the computation of total time to perform a task (whether it be typing a character or attaining a goal). The GOMS is also useful in that it simplifies many of the complex cognitive processes used in identifying an expert's mental model. This simplification serves two purposes: 1) it allows for consistency in almost every part of the GOMS analysis except for the actual cognitive process (refer back to the discussion on the "yellow pad" heuristic) and 2) once the mental processes are identified, a subsequent analysis can be performed to determine how varying the cognitive models affect the overall key layouts for either keyboard. It is this type of analysis that can be used to help understand how the mental model of an expert QWERTY typist can be analyzed to identify the type of mental model that would be most suitable for the Keybowl to maximize transfer of training.

Task Analysis

In performing a task analysis, it is first important to understand and develop a general task description of the typing task GOMS model:

- Task is to disseminate, manipulate and/or reproduce textual or auditory information.

- Piece of information is a word or character

- Position of key location

- Activation of key

Once the GOMS model is complete, it can be used to estimate the quality of the design. A task analysis that details and specifies the procedures used by an expert typist can be performed by analyzing several qualitative measures, predicting human performance with the design, and estimating execution times. Several of the following qualitative measures have been adequately addressed in the design of the Keybowl. The qualitative properties of the GOMS model include: (adopted from Kieras, 1988)

Naturalness of Design: Are the goals and subgoals clear to a new user or will the user be required to develop a new way of thinking to perform the task? The color coded concentric circle key layout is a highly visual layout which aids in making the Keybowl typing task easy to understand and use.

Completeness of Design: Is there a defined method for each goal and subgoal? In terms of typing, the method would be similar to the one discussed earlier.

Cleanliness of the design: Is there more than one method of key activation? No, key activation schema is the same for all character layouts– chordal.

Consistency of design: Is the method consistent? Addressing this issue requires analysis of similar goals being accomplished by similar methods.

Efficiency of the design: The most important and frequently used goals are accomplished by relatively short and fast-executing methods.

In addition to the aforementioned, a more traditional means of task analysis can be performed in basically the same manner to determine typing procedures used by experts. Experts can be queried in numerous ways as to how they perform the typing task. Direct questions can be used to form a basis for the analysis; refinement can be done as more and more experts are queried. Time and motion studies can be utilized to help establish the actual times of keying performance. Biomechanical methods can be employed to augment such measures and to provide information on how the motions between the two keyboards differ quantitatively. Perhaps the best way to evaluate an expert's typing task is to monitor their performance through an invisible software interface. Typists will not know they are being monitored. Data on character activation times, words per minute, number of errors per key or in total, and time to complete task can all be completed while an expert completes an actual task. These are just some of the ways in which task analysis can help specify procedures used by experts.

Determinants of the number of experts needed for GOMS analysis

The number of experts needed to perform an adequate GOMS analysis depends on several factors: If a statistical evaluation is to be performed after the GOMS analysis is complete, it would be important to develop the statistical design before performing the GOMS analysis. The statistical quantification is important to ensure consistency between the GOMS analysis and the statistical design. Depending on the statistical design (e.g., number of between means, Type I error, Type II error), the number of subjects can computed through various statistical algorithms (Cohen, 1977). Another posibility is to represent the mental models of at least 90% of the expert typist population. This could be done by randomly selecting experts until a 90%-95% similarity of the methods they use to perform a typing task are discovered. This may actually occur at a relatively low N due to the straight forward nature of the keying task. A final evaluation may be performed in the true spirit of GOMS analysis and the simulation annealing process– use only one expert (initially), model their process, and use simulation in conjunction with judgment calls to develop an optimal layout for any range of user. The keying task may be simple enough to effectively accomplish such a goal. Once the initial GOMS model is determined, expert typists need only to add to or modify existing methods, make or correct assumptions, and perform the analysis. This process also helps ensure consistency in the design.

Selection of an Appropriate Chording Scheme based on Biomechanical Considerations

In addition to developing an appropriate character layout, the way in which the domes are moved in reference to their relative chording scheme needs to be considered. In reference to the assignment of characters to chords (coding), two principles will be used: Hand movement dexterity, and uni-directional motions of the hand in performing the typing task. First, hand movement dexterity will be considered in the chord coding scheme. 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. This information may help determine the way in which the hand best moves. If the finger forces are highest in the thumb and index finger, the hand may have the highest dexterity in the fore, left, and fore-left positions in operating the bowl with the right hand. It is hypothesized that assigning the most frequently occurring letters to locations that have high pushing-force would facilitate performance when typing with the Keybowl. Response times and error rates per character are expected to be lower for chords that are produced using uni-directional motions when typing.

Human Performance Prediction

The previously devised GOMS model can predict learning and execution times of the Keybowl. This is most easily done at the standard primitives level (e.g., pressing a key). Therefore, the time to learn a method depends only on how long it takes to perform the sequence of steps in the method (Kieras, 1988). The actual learning time is dependent upon the details of the learning situation.

In addition to the preceding discussion, other models pertaining to execution times for type movements have been devised. One of the best known models for mouse movements is described by a derivation of Fitt's Law (Gillan, Holden, Adam, Rudisill, & Magee, 1990; MacKenzie & Buxton, 1992; Welford, 1968).

$$T_{pos} = K_0 + K \log_2(D / S + 0.5)$$

where

T_{pos}= *Positioning Time (seconds),*

D=Distance

S=Size of Target

K_0, *K=constants*

In this model, K_0 includes the time for the hand to adjust its grasp on the Keybowl and the time to make the selection of a single chorded move. A constant of $K \approx 0.1$ sec bit^{-1} (10 bits sec^{-1}) appears in a large number of studies on movement and is a fairly consistent measure of the information processing capacity of the eye-hand coordinate system (Card, English, & Burr, 1978). A straight line is found by plotting positioning of the Keybowl locations as a function of $\log_2(D/S+0.5)$. The slope of the line, K, should be approximately equal to 0.1 (Card, et al., 1978). Hence, regression analysis was used to determine the equation:

$$T_{pos} = 1.03 + 0.1\log_2(D/S + 0.5)$$

According to Card, English, and Burr, (1978) the standard error of this equation is 0.07 seconds and explains 83% of the variance of the means for each condition.

Estimating Execution Time

The time to execute a method depends on the time to execute the operators and on the number of cognitive steps, or production rules implemented (Kieras, 1988). Card, Moran, and Newell, (1983) suggested that 0.28 seconds for a keystroke can be used as a primitive external operator value for the operation of binary key. The operation of the Keybowl is assumed to take the same amount of time given that horizontal bowl displacement is similar to vertical key displacement. Biomechanical analysis and time and motion study methods are acceptable means to help estimate execution times on either keyboard. Execution times have also been proposed by Drury and Hoffmann (1992). The model developed by these authors demonstrated that, for a given key center spacing, the optimum key width for speed occurs when the gaps between adjacent keys is equal to the width of the tip of the finger.

Statement of Purpose

There are seven basic areas of concern in developing and evaluating an ergonomically developed keyboard, they include: Physical characteristics, human performance measures, the keyboard as a component of a system, repetitive strain injury evaluation, user population characteristics, cognitive modeling, and general related information such as biomechanical considerations. In general, a newly designed keyboard should not cause a new disability, aggravate an existing disability, or stress a user beyond their limitations. It should, however, incorporate and take full advantage of a person's capabilities. It is therefore hypothesized that the average variance in wrist deviation, in both flexion and extension and ulnar and radial movements, for the Keybowl typists is less than that of the QWERTY typists (H_a: $\mu 1 - \mu 2 < D_o$; $p<0.05$). It is also hypothesized that over a period of 5 hours of keyboard usage, mean performance levels (measured in GWPM) of QWERTY typists is greater than that of the Keybowl typists (H_a: $\mu 1 - \mu 2 > D_o$; $p<0.05$). In an attempt to round out the study, and provide the necessary supporting information for appropriate hypothesis evaluation, the NASA Task Load Index (TLX) was used to determine respective keyboard workloads and a seven point Likert scale questionnaire was developed and used to evaluate user satisfaction and muscle fatigue in the hand, wrist, and shoulder when using the keyboards.

Method

Workstation Set-up

It is extremely important to account for individual differences not only for keyboard design but also for the environment in which typing takes place. It should be recognized that typists, coupled with their workstation, are very vulnerable to ergonomic shortcomings that affect the typing task (Grandjean, 1988). Moreover, workstation personnel are more apt to encounter strained physical positions, poor display characters, and inadequate lighting than are others in the office environment. All of these things may, and often do, affect typing performance (see Sauter, Schleifer, & Knutson, 1991). The design of the workstation is used as a generic term for encompassing all things that may influence the typing task. Factors related to seating comfort, lighting, VDT character resolution and size, etc. all play an extremely important role in eliminating CTS. In an effort to provide maximum comfort and to eliminate many of the inherent biases in poor working posture on typing performance, several Workstation/VDT guidelines were adopted from an amalgamation of four sources of information: *The American National Standard for Human Factors Engineering of Visual Display Terminal Workstations (ANSI/HFS 100-1988), Design of VDT Workstations* (Grandjean, 1988), *Ergonomics in Computing Offices (Grandjean, 1987), and The Relationship of Working Posture to Performance in a Data Entry Task* (Swanson & Sauter, 1993). These references clearly specify workstation conditions that represent accepted principles of human factors engineering for the computer monitors, chairs, desks, and environmental factors affecting the typing task. Researchers from anthropometry, biomechanics, psychology, and other related disciplines have set forth these basic guidelines related to VDT function and operation. The guidelines focus primarily on optimizing human performance. Seat height, keyboard height, screen height above floor, visual angle, and visual distance are just a few of the metrics that have been studied to establish a preferred setting for eye level. Eye level is only one of many aspects that has been extensively researched. Although extremely important, it is beyond the scope of this research to delve into each one of these general guidelines. However, to generally classify the major components of workstations design, the following groups were identified as having major effects on the keyboarding task. The application of these guidelines are relevant to factors that influence text processing, data entry, and data inquiry for seated operations.

- Environmental: lighting, air quality.
- Postural: Seating height, viewing angle; design work surface heights, orientations, and reach length to maintain neutral positions.
- Physical: general health, stress/strain; distribute load over as many muscle groups as possible, avoid repetitive gripping actions, e.g., using the mouse.
- Biomechanical: strength, reach; avoid extreme flexion or extension of wrist. Keep forces low during rotation or flexion of joint.
- Physiological: adequate breaks.
- Psychological: work ethic, control.

As with VDT considerations and guidelines, the keyboard can not and should not be analyzed as a single system or component. The keyboard is to be considered as part of an overall system in which the user & VDT workstation environment need to be integrated and analyzed as a system (Kroemer, 1993). With respect to keyboard design, the majority of guidelines adapted for this study were taken from five sources: *The American National Standard for Human Factors Engineering of Visual Display Terminal Workstations (ANSI/HFS 100-1988), Design of VDT Workstations* (Grandjean, 1988), *Ergonomics of Workstation Design* (Kvalseth, 1983), *Preferred Height and Angle Settings of CRT and Keyboard for a Display Station* (Miller & Suther, 1981), and *Avoiding Cumulative Trauma Disorders* *in Shops and Offices* (Kroemer, 1992). Metrics pertaining to keyboard height and slope, placement, key travel, key force, keying feedback, and keyboard stability were used in selecting an appropriate QWERTY keyboard and were used in building the Keybowl prototype. Guidelines related to keyboard profile (e.g., rows being arranged in a stepped, dished, sculptured, or flat profile), key spacing (i.e., center line distances between adjacent keys), and keytop shape and size were considered only for the QWERTY keyboard. The QWERTY keyboard selected for this study was an Apple standard keyboard. The keyboard meets or exceeds all guidelines presented in the ANSI/HFS 100 standard or related articles (Grandjean, 1988; Kroemer, 1992; Kvalseth, 1983; Miller & Suther, 1981). The Keybowl was developed using the design principles that appropriately apply to its development. Several of the evaluation criteria used in selecting the QWERTY keyboard could not be applied to the Keybowl. Therefore, the Keybowl was developed with congruent metrics to the QWERTY keyboard where applicable. Moreover, it has several characteristics that are similar to the QWERTY keyboard. Both had a 'key' force of approximately 0.7 N and a key displacement of 4 mm. Keybowl design was kept as close to QWERTY specification to control for statistical confounding. In addition to force and displacement considerations, character size and font was the same for each keyboard for easy visual 'key' activation reference. The Apple QWERTY keyboard that was used utilized a font size of approximately 14 points and resembles a Helvetica font. Therefore, the Helvetica 14 point font was used on the Keybowl to ensure consistency.

Participant Pre-Screening

In an effort to provide representative typing population performance and ergonomic measures, subjects were selected based on their experience with the

QWERTY keyboard. Proficient typist capabilities were identified to determine which typists have the most similar typing task characteristics (i.e., typists typing 40 wpm or greater (Card & Moran, 1980)). In comparing performance measures in different keyboards, methodological elements, as defined by Conrad and Longman (1965), were considered; subjects were drawn from a population with homogeneous relevant qualities. These guidelines were adopted in studying the Keybowl to ensure a valid comparison. Participant screening continued until 30 candidates were found that had comparable typing performances (see discussion on power in Analyses section). Each subject was required to be free from wrist and upper arm injury (see screening questionnaire and related information in Appendix A) and was pre-screened for typing competence, that is, all subjects were required to be proficient QWERTY typists (i.e., touch typists typing at least 30 GWPM see Appendix B). In an effort to eliminate letter or word recognition difficulty and to avoid language interference, all subjects were required to be native speakers of the English language. After consenting to participate, subjects were given oral instructions on what was expected for the study and were shown the features of each respective keyboard and the associated task requirements.

Subjects

Thirty touch typists (nineteen females and eleven males) between the ages of 21 and 46 (mean= 25.3, s.d. =5.5) participated in the research. Pre-experiment typing performances ranged from 22 to 65 GWPM (mean= 41, s.d. =12). Subjects were randomly separated into two groups, one group using the QWERTY keyboard, the other the Keybowl. Educational Testing Service (ETS) spatial tests and memory tests, MV 1/1 and MV 1/2 and MV 2/1 and MV 2/2 respectively, were used to determine subjects spatial and memory adeptness. The tests required subjects to answer as many of 16 questions as possible in a four minute time period. The score was determined by dividing the number of questions answered by the number correct. Subjects were not penalized for not answering a question. In addition to the memory and spatial tests, subjects were required to take a 1 minute typing test for prescreening purposes. The typing test was taken from a typing text (Marks, 1985). Each subject was given coursework extra credit for participating in the study.

Equipment

Two Macintosh computers configured with 8 megabytes of random access memory (RAM), 250 megabytes of hard disk space, and 13" high resolution color monitors were used in the study. The two computers were used to collect data: One used to collect the subjects typing performance data, whereas the other was used to collect wrist movement data. Performance data was collected via keystrokes through the QWERTY keyboard or the Keybowl. In terms of keyboard equipment, half of the subjects used the Keybowl prototype as their main input device and the other half used a standard QWERTY keyboard developed by Apple Computer. No hardware modifications were made to the Apple keyboard.

Penny and Giles electrogoniometers (Model M110) were used to measure wrist movements in the flexion and extension and ulnar and radial planes. Goniometer data was collected at a rate of 6 seconds for each wrist. Sampling at six times a second allowed for adequate capture of the full range of motion during the typing task. The electrogoniometers were interfaced to the Macintosh through the use of an analog to digital (A to D) data acquisition board. In terms of data transfer and acquisition, the electrogoniometers are capable of sending data continuously, the National Instruments data acquisition board is capable of gathering data every 9ms, and the Macintosh captures and stores data every

20ms. Total throughput was extremely high thereby making acquisition of data from all 4 goniometer channels basically continuous. Goniometer data were recorded to a data file through a software data acquisition package called LabView. LabView allowed for the creation of a virtual instrument for collecting, plotting, and analyzing the goniometer data.

A streamlined prototype of the Keybowl was used for experimentation (see Figure 18); a 16 character version of the Keybowl allowed users to type the 16 most commonly used letters of the English alphabet (A, E, R, T, F, D, C, S, U, I, O, P, L, M, N, and H). Both hands were required to input characters using the Keybowl, one hand for each bowl. The reduced character set was used to avoid long training periods yet establish ergonomic and typing performance baseline measures. The character ring around each dome contains eight characters each defined by a discrete movement of the bowl: fore, aft, left, right, and to the 45 degree positions. Bowl movements in any of the eight respective positions on either bowl allowed the user to type one of the sixteen characters. The eight position's were representative of the characters typed on the QWERTY layout. For example, the left hand Keybowl controls the same keys that are controlled by the left hand when typing on the QWERTY keyboard. The Keybowl's counterpart, the Apple QWERTY keyboard, was modified through software control to provide the same streamlined functionality as the Keybowl (i.e., the same 16 characters, with all others disabled through software control). Keys other than the 16 could be pressed but no character would be output (see Figure 19).

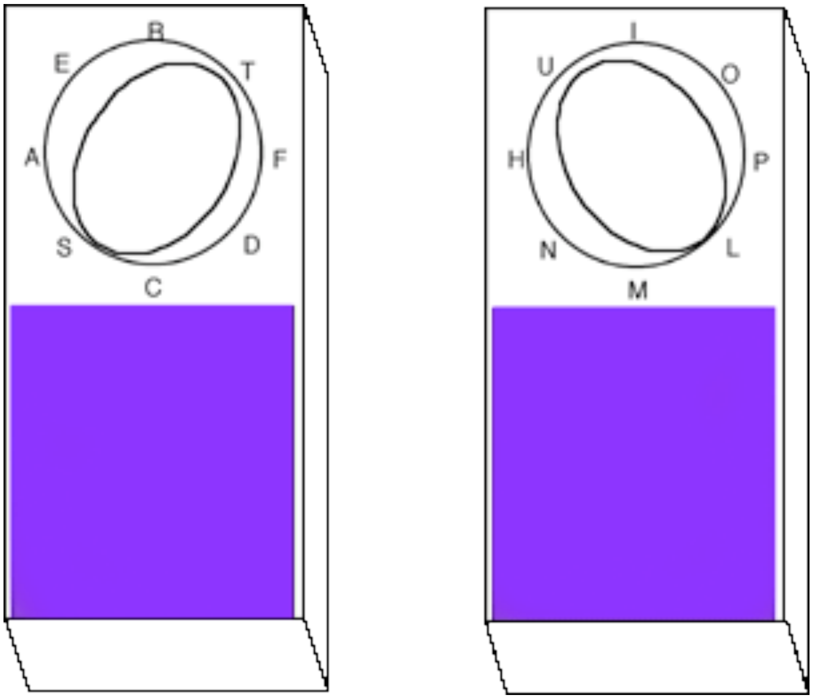


Figure 18. Sixteen character prototype version of the Keybowl.

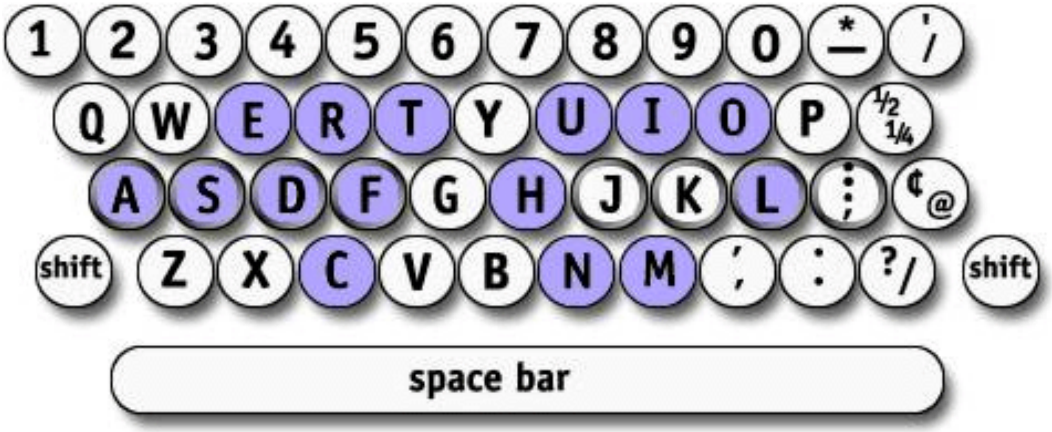


Figure 19. Identification of characters used in the study (shaded).

Goniometer Considerations

Two types of motion were analyzed to determine the amount of wrist movement: Palmar flexion (flexion) and dorsiflexion (extension) which take place around a transverse axis in the sagittal plane and radial and ulnar (adduction and abduction respectively) deviation which occur around an anteroposterior axis in the frontal plane (Kapandji, 1982). Alignment of the goniometer's end blocks is important for accurate measurement (see Cambridge, 1990; Moore, 1984). Scott and Trombly (1989 cited in McDonald, 1992), and West (1945) described a method in which a goniometer is aligned with the joint axis of rotation. This method was proposed to match joint motion as much as possible. Several researchers are against such methods due to difficulty in accurately identifying and analyzing (due to shifts throughout normal ranges of motion) the axis of rotation (Miller, 1985; Scott and Trombly, (1989 cited in McDonald, 1992)).

The goniometers operated as strain gauges in which the output signal represented the summation of strains along the length of the wire (Nicol, 1988). The goniometer therefore recorded the relative angular movements of one endblock in relation to the other. Penny and Giles, the makers of the goniometers, reported that the measured angular displacement of a joint can be done irrespective of the linear movements of the endblocks which occurs when the goniometer is poorly aligned with the axis of rotation (Penny & Giles, 1990). It is therefore not necessary to attach the goniometers along the aforementioned joint axis of rotation. The elgon can be placed over the wrist joint, rather than on a medial or lateral border. Wrist motion conventions are such that wrist extension motions and left hand radial motions were recorded as (+) motions, whereas wrist flexion and right hand radial motions were recorded as (-) motions (see Figure 20).

With all the visual, memory, cognitive, and motor processes used in typing, it is theorized that the information processing time from first seeing a character to typing it on a keyboard is approximately every 0.67 seconds (see the

Human Information-Processor; Card, Moran, & Newell (1983)). Sampling twice every second would adequately capture the information processes proposed by Card, Moran, and Newell (1983). It is believed, however, that as typists gain proficiency, other processing dynamics such as reduced visual scans, quicker character retrieval from long term memory, etc. become much faster than what is proposed. How much faster depends on the experience of the typist (recall that the subjects in this study typed an average of 40 wpm). In addition, there could be several interim movements that the hands make between keystrokes. These motions also need to be captured. The sampling rate was therefore increased from 2 times a second to 6 times a second to guarantee that all wrist motions were captured.

Design and Procedure

Research was conducted in an established and commonly used educational setting. The evaluation of the Keybowl was based on training methods used by the majority of typing teachers (i.e., sixty gross words per minute = 300 keystrokes per minute = 18,000 keystrokes per hour. All guidelines for computer comfort were instituted to the extent possible and all instrumentation was used in accordance with manufacturer specification.

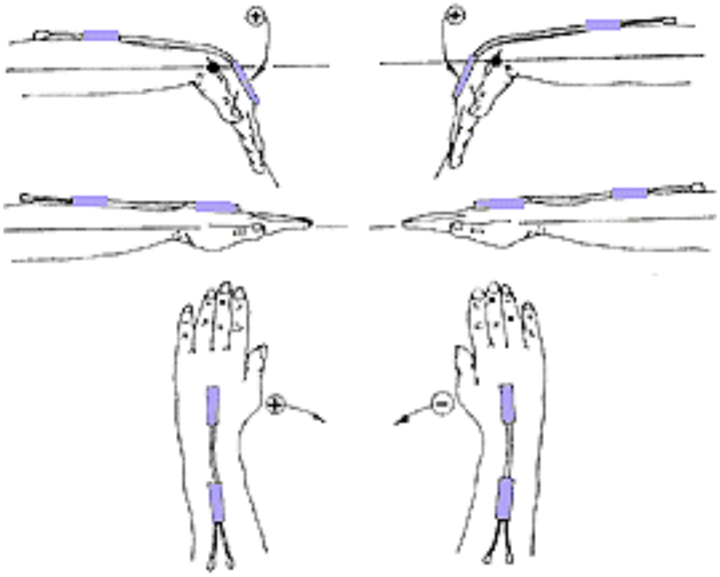


Figure 20. Goniometer/Hand movement conventions.

Start Session

With the forearm fully pronated and wrist fully flexed, the goniometers were attached to the subject's hand and arm (see Figure 21). The telescopic endblock was secured to the dorsum of the hand, over and in line with the long axis of the third metacarpal. With the wrist fully flexed, the fixed endblock was pulled proximally, until the elgon was at its maximum length. The fixed endblock was then attached to the dorsal surface of the forearm parallel to the long axis of the radius. This attachment ensured that the measuring element was centered over the dorsum of the wrist. Once attached, the hands were held straight and in line with the arm (usually done by resting the hand and arm flat on the arm of chair) and the goniometers were "zeroed". This process allows the electrogoniometers to be set to 0 degrees when the hand is in a zero flexion/extension position and a zero ulnar/radial position. Once the goniometers were positioned properly, the subjects were instructed to enter their subject ID into the computer.

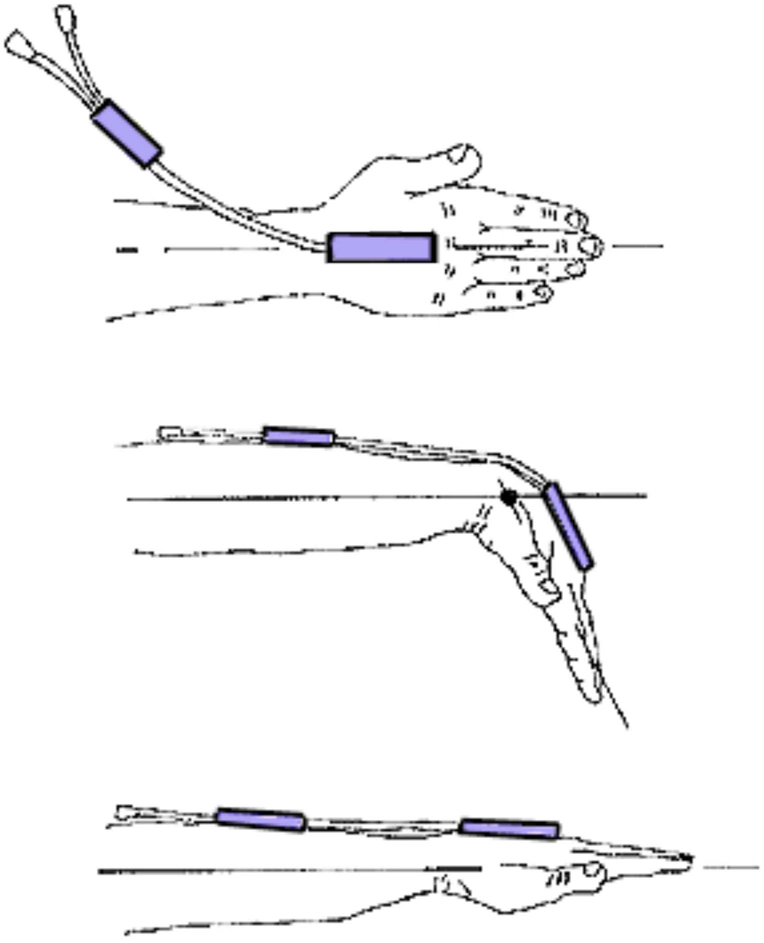


Figure 21. Location of attachment procedure of goniometers transducers.

Subjects were required to enter their ID (which was typically their first name), confirm that their ID was correct, and press return to initiate a software controlled random character/word generation process. The subject ID had a dual purpose. ID's were used to identify which session the subject was currently performing and for creation of the file to which the data was to be written (data files were sequentially written according to the session being performed (session

1 for Pete would create a data file named pete1). Once a randomly generated process was initiated, the subject was given the Keybowl or Keyboard from which to type. After a few seconds the computer completed the random generation of elements (either characters or words), beeped, and placed the cursor next to the first character on the screen. With the goniometers attached and the random characters/words generated, the computers were then ready to record the ergonomic and performance data. The computer software was written such that the first character typed started an 18 minute, 45 second timer. Within 2 seconds of the subject entering the first character for the performance data collection, the goniometer data collection process was started. This was done manually by the experimenter. Upon typing the first character, the cursor bar would move to subsequent characters and the subject simply had to type the character immediately to the right of the cursor. If an incorrect character was typed, the character would change to the incorrect character typed and the cursor bar would move to the next character. If the correct character was typed, the subject would see no change in the character and the cursor would move to the next character. Typing errors could not be corrected during the session. Spaces were not a factor; after each character in stage 1, or after each word in stage 2, the cursor automatically moved to the next character or word. This process continued for 18 minutes and 45 seconds. After the 18 minute 45 second timer ran out, the session concluded by saving the collected session data and terminating the program. Data collected during the session included the letter displayed, letter typed, a binary correct count, and time between keystrokes. The computer captured performance data at the rate of approximately 0.016 seconds per character.

Stages of Testing

Subjects were required to type for 16 sessions, one session per day (subjects were required to type at least 3 days a week). They were instructed to type as quickly and as accurately as possible. For each session subjects typed 18 minutes and 45 seconds (total time of keyboard usage was 5 hours). In the first eight sessions subjects were required to type random characters. In the second eight, random words were typed. A similar procedure was implemented for sessions 9-16, the random word sessions.

Two stages of testing were devised to track subject performance and to help them gain typing proficiency. The sessions administered to the two groups of subjects included identical material and the experimenter was the same for all subjects to avoid experimenter effects between subjects. In the first stage of testing, sessions 1 through 8, subjects were required to type random characters. The random characters chosen for stage 1 were the most commonly used characters in American English (Guinness Book of World Records, 1992), they are:

e, t, a, o, i, n, s, r, h, l, d, c, u, m, f, p

The 16 characters were chosen because they represent the most often used characters and thereby provide the best estimation of actual typing speed for a reduced character set. In addition, it has been observed that the most often occurring characters of a language lessen the mental and physical workload on the operator of the device (Gopher, et al., 1984). One half of the characters (e, t, a, s, r, c, f, and d) are typed using the left hand whereas the remaining characters (o, i, n, h, l, u, m, and p) are typed using the right hand. Each Keybowl was developed such that the same 8 characters operated by left and right hands for

QWERTY typing are identical to those typed using the Keybowl. Additionally, location and hand movements in both keyboards are similar (e.g., typing the letter P on a QWERTY keyboard or the required a left hand movement toward the upper right). This was done primarily to take advantage of the QWERTY typists mental model (findings based on GOMS analysis). Each of the eight sessions was comprised of 8,800 randomized characters with each of the 16 characters occurring equally often. Subjects were presented the 8,800 random characters one screen at a time; each screen contained 1330 characters (38 columns x 35 rows). Eight thousand eight hundred characters guaranteed that even a typist typing 80 WPM would not finish typing the characters, or words, before the session ended. Stage two, the random word stage, was comprised of 7,840 random words per session. Words were randomized from the following lexicon:

> **add, is, for, hat, run, tall, this, that, form, call, his, pump, such, cuffs, final, catch, humid, people, dinner, common, summer, puddles, popcorn, different**

The 24 word lexicon is a composition of exactly 7 of each of the 16 characters (i.e., 16 letters x 7 =112 characters. The 112 characters make up the 24 word lexicon). This was done to ensure that each of the characters occurred as equally often in the random word stage as in the random character stage. The words chosen also reflect a distribution of characters found in typical everyday text (i.e., average word length is approximately 5 characters) (see Figure 22). Each session displayed approximately 420 words per screen. The screen automatically scrolled when the last character of the screen was typed in either stage.

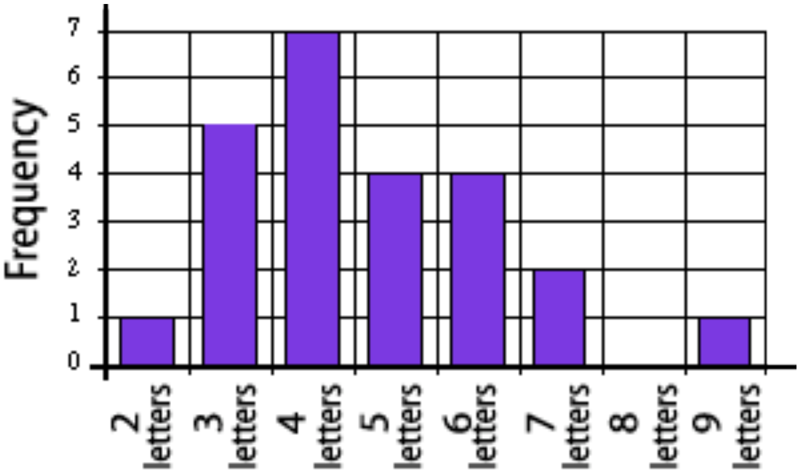


Figure 22. Random word letter frequency

Subjective Workload Evaluation: NASA Task Load Index (TLX)

The NASA Task Load Index (TLX) is a "multi-dimensional rating performance that provides an overall workload score based on a weighted average of ratings on six subscales: Mental Demands, Physical Demands, Temporal Demand, Own Performance, Effort, and Frustration" (Hart & Staveland, 1988). The NASA-TLX consists of two parts: A ratings procedure and a weighting procedure (see Appendix C). Subjects were required to complete a rating procedure after each session, and a weighting procedure after every fourth session. Scores from the rating procedure were then adjusted according to the weighting factors. A weighted score was then computed for each subject for each session.

Questionnaire

The questionnaire used in this study (see Appendix D) was used to ascertain whether or not experiences were similar between the two keyboard subject groups. Twenty one questions pertaining to performance, typing satisfaction, personal satisfaction, muscle fatigue, and ease of use of the keyboard, were asked of each subject after each stage.

At the end of the each stage, each subject in each group was required to read the instructions and respond to 21 bipolar subjective rating scales that addressed issues related to the subject's respective keyboard. The subjective ratings stage serves two objectives: (a) to allow a comparison of keyboard characteristics, and (b) to help obtain information that could be used in improving the design of the Keybowl.

Experimental Design & Analyses

Ergonomic evaluation of the Keybowl and QWERTY keyboard was performed by measuring left and right hand flexion and extension and ulnar and radial wrist movements using the aforementioned electrogoniometers. Ergonomic data was collected during each of the 16 sessions (Figures 23, 24 , 25 and 26). The data were analyzed using a repeated measures 2 x 2 x 2 x 4 x 8 mixed model analysis of variance (ANOVA). For ergonomic evaluation, keyboard type and gender were between subject factors whereas stage, wrist movement (analyzed in both flexion and extension and ulnar and radial planes), and session are the within subject factors, respectively. Variations of the same mixed model ANOVA were used to analyze the other sets of data (detailed in the Results section) (see Figure 27).

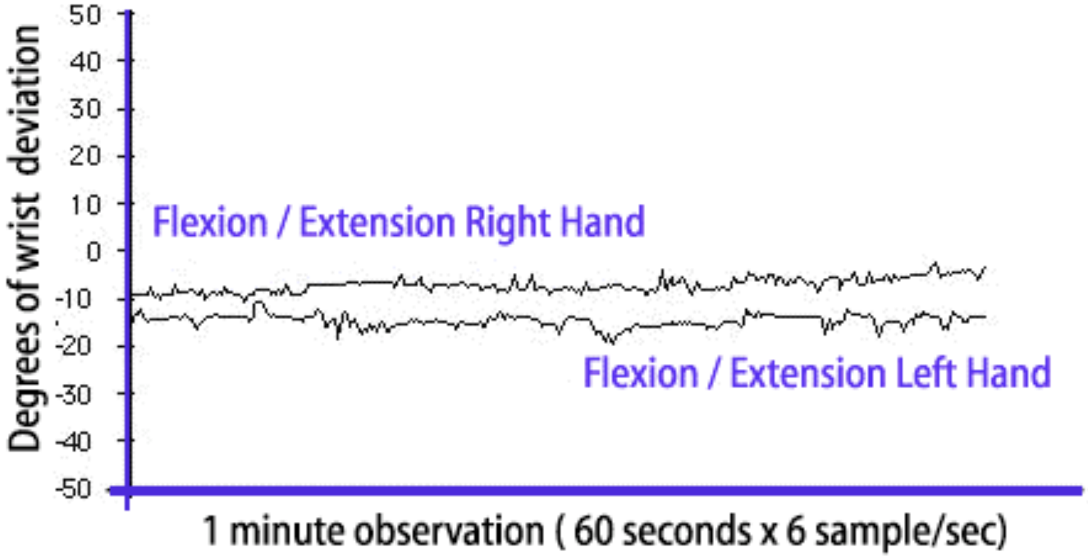


Figure 23. Representative Flexion and Extension Movements of a Keybowl user.

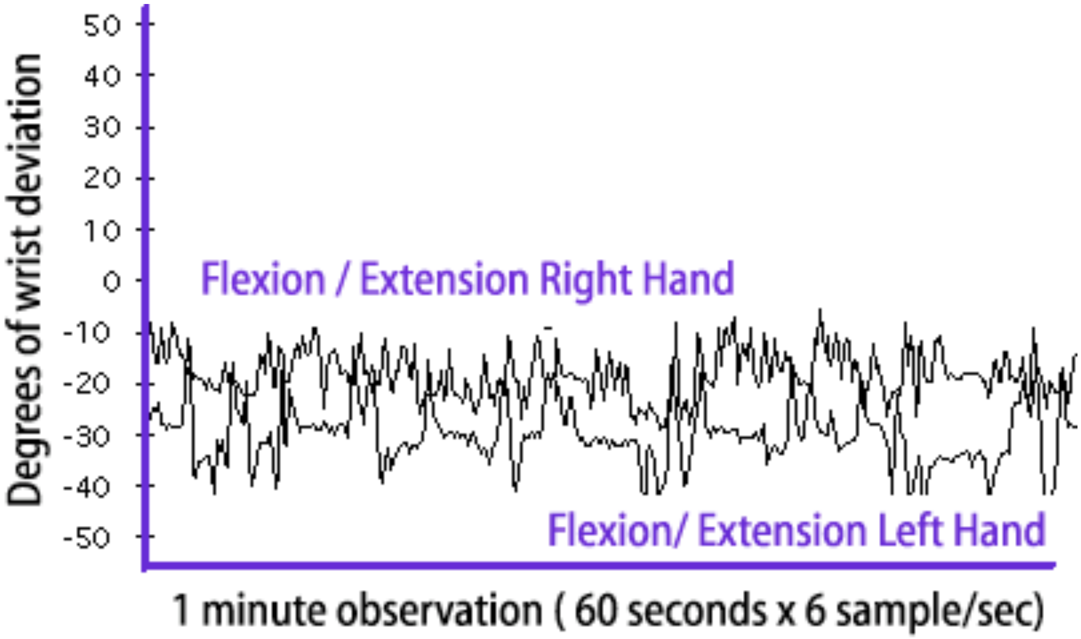


Figure 24. Representative Flexion and Extension Movements of a QWERTY user.

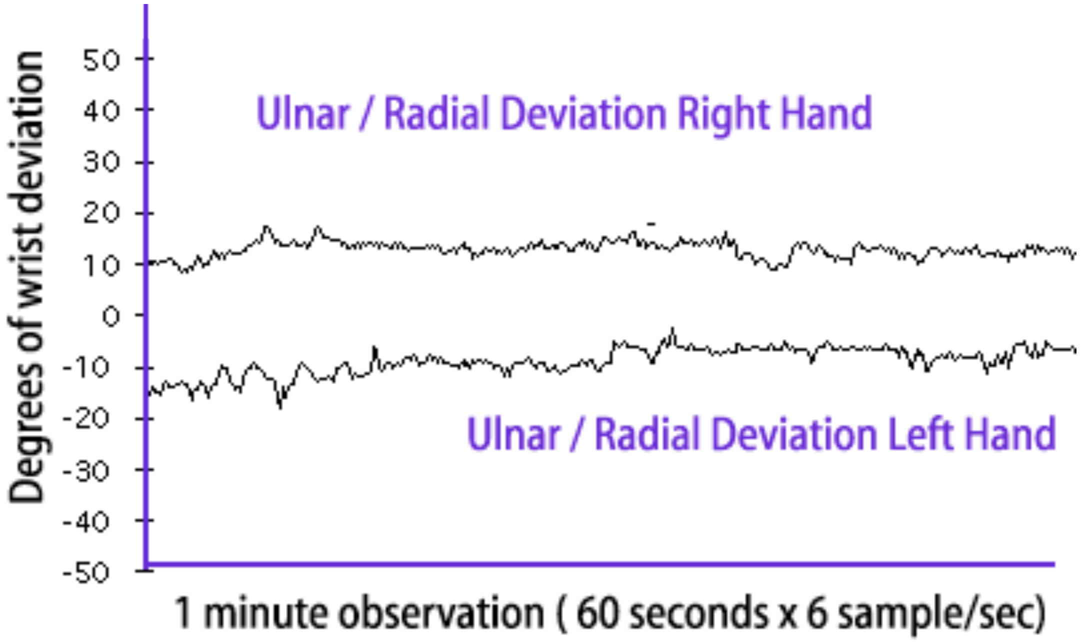


Figure 25. Representative Ulnar and Radial Movements of a Keybowl user.

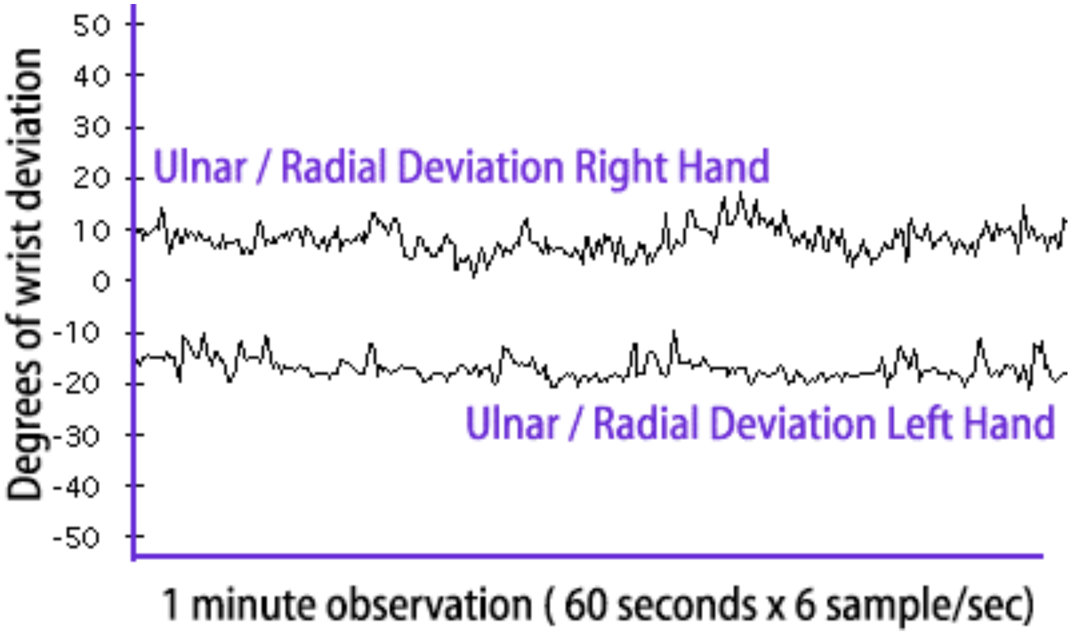
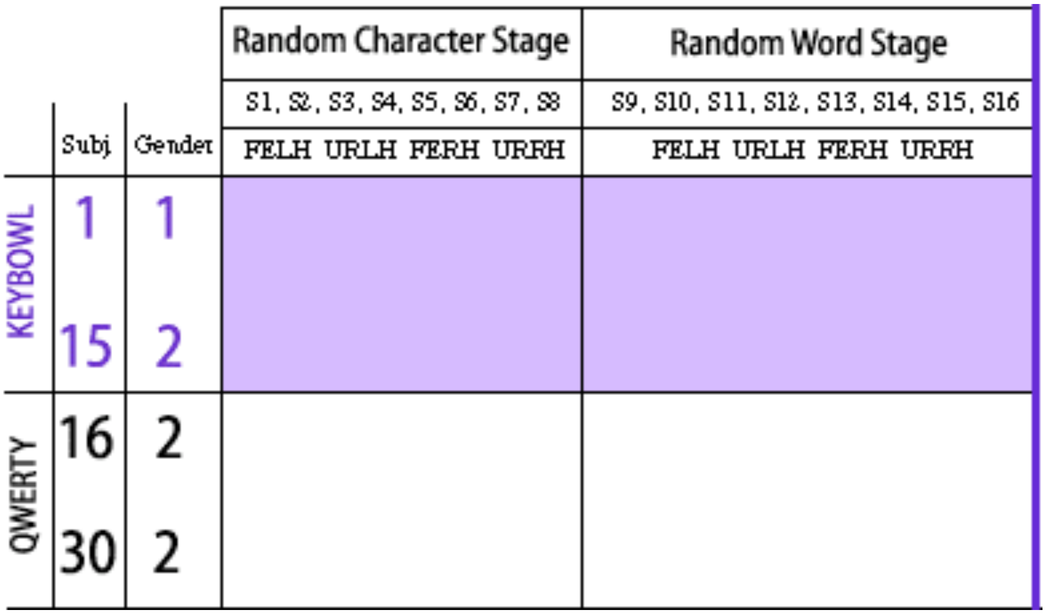


Figure 26. Representative Ulnar and Radial Movements of a QWERTY user.



			Random Character Stage	Random Word Stage
			S1, S2, S3, S4, S5, S6, S7, S8	S9, S10, S11, S12, S13, S14, S15, S16
	Subj	Gender	FELH URLH FERH URRH	FELH URLH FERH URRH
KEYBOWL	1	1		
	15	2		
QWERTY	16	2		
	30	2		

Figure 27. 2 x 2 x 2 x 4 x 8 Statistical Design

The design was developed to analyze numerous hypothesized ergonomic and performance differences between the Keybowl and the QWERTY keyboard. The analyses are composed of two stages of performance evaluation and one ergonomic analysis. Both analysis includes objective and subjective components.

In determining appropriate power, Cohen (1977) sets forth an adequate approximation for two means based on alpha level and sample size. The following formulae were used to compute power by determining the difference between independent means (the mean of the QWERTY keyboard data and the mean of the Keybowl data, for example):

$$\gamma = \frac{(\mu_1 - \mu_2)}{\sigma} \text{ and } \delta = \gamma\sqrt{\frac{N}{2}}$$

where γ is the effect size, μ_1 and μ_2 are the independent means, σ is the standard error, and N is the number of cases in any one sample.

Based on prior studies of chordal keyboards versus QWERTY keyboards, a rough approximation of γ was found. Examining sample means and variances from the study done by Fathallah (1988) an approximation for the current study was made. From the available data, the γ value, computed using the above formula and Fathallah's data, was .80 (μ_1=39, μ_2=27, σ=15). Solving for δ, the obtained power value is 0.789 for a two-tailed test. Therefore, if the investigation is run with 24 subjects, and the δ is correct, then there is a 78.9% chance of actually rejecting the null hypothesis.

Dependent Variables

For proper evaluation and in order to make comparisons between the two keyboards under consideration, objective and subjective data were gathered from each subject. Objective performance measures include character presented, character typed, a 0 value for characters properly entered and a 1 for character errors. Data were collected and used to determine the typing performance of each subject. Further, objective biomechanical measures of wrist flexion and extension and ulnar and radial movements were collected from each subject. These performance and biomechanical measures were collected during the 16 stages of experimentation.

For the random character stage (stage one), the dependent measures collected from each subject were gross words per minute (GWPM). The same dependent measures were collected for stage two, the random word stage. In terms of biomechanical evaluation, dependent measures include degree of flexion or extension wrist movement in the vertical plane and degree of ulnar and radial wrist movement in a horizontal plane.

Subjective measures, related to the different features of the subjects respective keyboard, were obtained from each subject. Subjects were asked to respond to approximately twenty bipolar scales corresponding to their respective keyboard. The NASA-TLX (Hart & Staveland, 1988) was administered after each session to gauge overall workload.

Results

Analyses were broken down into five general groups: 1) group homogeneity, 2) ergonomic considerations, 3) typing performance & learning, 4) workload, and 5) subjective evaluation. Each group was analyzed independently of the others. (Refer to Appendix E for complete ANOVA summaries).

Group Homogeneity Statistics

Several analyses were performed to determine how the two groups compared in terms of spatial, memory, and typing abilities. The two subject groups were not significantly different with regard to spatial and memory abilities. Within group spatial test scores (between MV 1/1 and MV 1/2) for the QWERTY keyboard group, scores averaged 84% (s.d. 14.5%) whereas scores on the memory tests (between MV 2/1 and MV 2/2) averaged 84% (s.d. 13.45%). For the Keybowl group, spatial test scores averaged 83% (s.d. 10%), and memory test scores averaged 84% (s.d. 16.7%). The between group spatial test scores averaged 83% (s.d. 10%) whereas the memory test scores averaged 84.3% (s.d. 12%). A one way ANOVA examining spatial and memory abilities revealed no statistical difference between the two groups ($\underline{F}(1,28)=0.1$, $\underline{p}>0.05$) for spatial abilities, and ($\underline{F}(1,28)=0.0001$, $\underline{p}>0.05$) for memory abilities.

The average pre-experiment QWERTY keyboard typing speed for the Keybowl subjects was determined to be 40 GWPM (s.d. =11). Typists in the QWERTY keyboard group typed an average of 42 GWPM (s.d. =14). A one-way ANOVA examining pre-test typing proficiency revealed no significant difference detected in typing speeds between the two subject groups as determined by a one minute typing test (F(1,28)=0.0021, p>0.05).

Ergonomic Considerations

Ergonomic evaluation of the Keybowl and QWERTY keyboard was performed by analyzing goniometer data from the left and right hand movements. The two planes of motion (flexion/extension and ulnar/radial) were the dependent measures and were analyzed independently. This served two purposes: 1) to eliminate any confounds for movement crossover, and 2) to analyze the flexion and extension movements separately as they are believed to be main contributors to CTS. The data were analyzed using a repeated measures 2 x 2 x 2 x 2 x 8 mixed model analysis of variance (ANOVA). Keyboard type and gender were between subject factors whereas stage, wrist movement, and session were the within subject factors, respectively. Dependent variables include wrist motions in the flexion/extension plane and motions in the ulnar/radial plane.

Flexion/Extension Movements

The flexion and extension movement data were analyzed using a repeated measures 2 x 2 x 2 x 2 x 8 mixed model analysis of variance (ANOVA). Keyboard type and gender were between subject factors whereas stage, flexion and extension wrist movement, and session were the within subject factors. There was a significant difference detected in wrist movements between the two subject groups (flexion/extension movements of the left and right hands combined (F(1,26)=58.34, p<0.0001)). The Keybowl users' wrist deviations averaged 2.7 degrees in the flexion/extension plane whereas the QWERTY keyboard users' wrist deviations averaged 15.4 degrees (see Figure 28 and Table 4). Overall, wrist movement was reduced by an average of 82.5% in the flexion/extension plane when using the Keybowl. Also found was a significant difference between male and female flexion and extension wrist movements; females had significantly greater flexion and extension wrist movements than did males (F(1,26)=10.52, p<0.0035). In analyzing the gender by keyboard interaction, a significant effect was found only for the QWERTY group between males and females (F(1,26)=5.43, p<0.028). A test of simple effects at the 0.05 level of significance revealed that females had significantly higher flexion and extension wrist movements when typing with the QWERTY keyboard compared to the males using the QWERTY keyboard (F(1,26)=7.771, p<0.009). There was no significant difference detected between male and female flexion and extension movements when using the Keybowl.

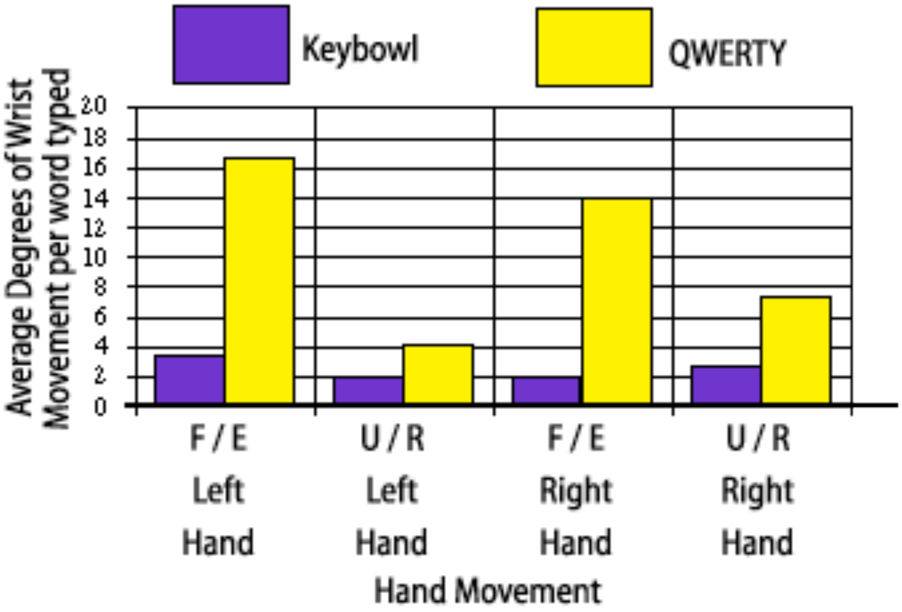


Figure 28 . Average wrist movements (in degrees) for the Keybowl and QWERTY groups.

Table 4.

Average range of movement (in degrees) for the Keybowl and QWERTY keyboard typing.

	Keybowl	QWERTY Keyboard	% Difference
Flexion and Extension of Left Hand	3.34	16.72	80%
Ulnar and Radial of Left Hand2.01	4.18	52%	
Flexion and Extension of Right Hand	2.05	14.05	85%
Ulnar and Radial of Right Hand2.68	7.45	64%	

The keyboard main effect was statistically significant (F(1,26)=58.34, p<0.0001). QWERTY typists had significantly greater flexion and extension wrist motions than Keybowl typists. Gender was also statistically significant; females had greater flexion and extension wrist motions than males (F(1,26)=10.52, p<0.003). Session was also significantly different (F(7,182) = 3.56, p<0.0013). A Newman-Keuls range test was run to determine which sessions were significantly different. Sequential analysis (i.e., session 1 compared to 2, 2 to 3, etc.) reveals no significant difference between sessions. The significant differences occur when comparing the first session of the random character stage to latter sessions of the random word stage.

A significant three-way (Stage x Hand x Session) interaction was found (F(7,182) = 2.19, p<0.0369). For ease of interpretation, Figure 29 shows this three-way interaction as 2 two-way interactions, one for each stage. The three-way interaction indicates that right and left hands were significantly different in the random character sessions and in the random word sessions. Simple effects tests of the interaction showed that hand flexion and extension movements were not consistent throughout the random character sessions. Results indicate that the largest variation in wrist movement for stage 1 between hands was in session 1 (F(1,182) = 27.462, p<0.0001), significant differences also existed in sessions 2 (F(1,182) = 8.095, p<0.005), 3 (F(1,182) = 6.234, p<0.0135), and 4 (F(1,182) = 7.29,

$\underline{p}<0.008$). Left and right hand movements between sessions were also significantly different. For stage 2, the random word stage, left and right hand flexion and extension movements were significantly different for all eight sessions. Only the left hand, however, was significantly different among sessions. The right hand flexion and extension movements were not significantly different in sessions 9 through 16.

A significant interaction between stage and keyboard was also found ($\underline{F}(1,26)=11.62$, $\underline{p}<0.002$). A test of simple effects revealed that significantly higher flexion and extension wrist movements were required for the random word stage as compared to the random character stage when typing with the QWERTY keyboard. There was no significant difference between the two stages for the Keybowl group (see Table 5).

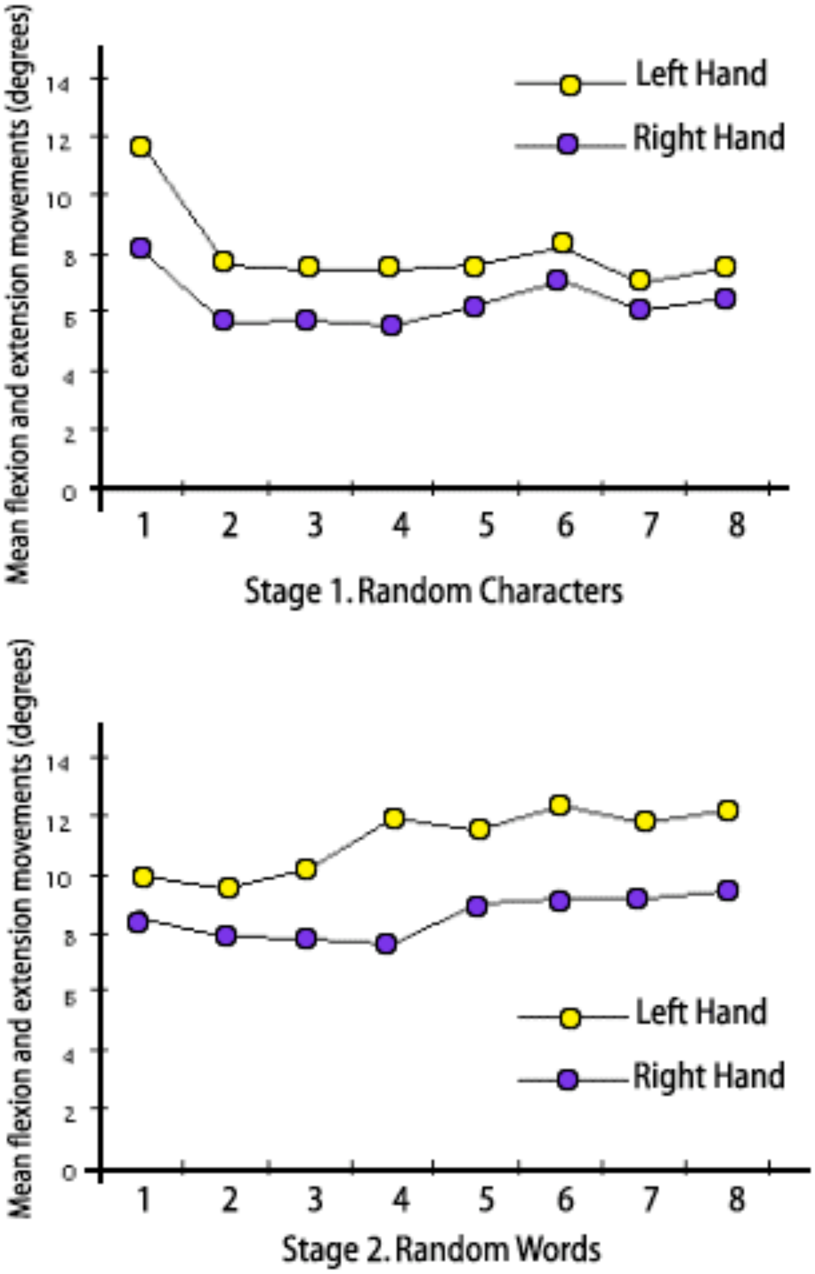


Figure 29. Mean flexion and extension movements as a function of stage, hand, and session.

Table 5.

Tests of simple effects table of stage x keyboard interaction

Source	DF	SS	MS	F	P
Keyboard at stage one	1	6000	6000	19.044	<0.0001*
Keyboard at stage two	1	11877.89	11877.89	37.701	<0.0001*
Stage at Keybowl	1	23.064	23.064	.290	>0.05
Stage at QWERTY	1	1319.762	1319.762	16.606	<0.0004

*Satterthwaite MSE = 315.059

*Satterthwaite DF (DEN) 33.352

Ulnar and Radial Movements

With regard to ulnar and radial movements, there were several parallel findings to those found in the flexion and extension movement results. The ulnar and radial movement data were analyzed in the same way the flexion and extension data were analyzed. The data were analyzed using a repeated measures 2 x 2 x 2 x 2 x 8 mixed model analysis of variance (ANOVA). Keyboard type and gender were between subject factors whereas stage, ulnar and radial wrist movements, and session were the within factors. Even with a much reduced range of motion in the ulnar and radial plane compared to the flexion and extension plane (see Figure 4), a significant difference between the Keybowl and QWERTY keyboard ulnar and radial movements was found ($F(1,26) = 15.99$, $p<0.0005$). The QWERTY keyboard had significantly higher ulnar and radial hand movements when compared to the Keybowl. Overall wrist movement was reduced by an average of 58% in the ulnar/radial plane. The users' wrist deviations averaged 2.3 degrees in the ulnar/radial plane whereas the keyboard users' wrist deviations averaged 5.8 degrees in the flexion/extension plane (see

Figure 28). Ulnar/radial movements of the left and right hand were also found to be significantly different (F(1,26)=10.37, $p<0.0034$). The left hand had significantly less ulnar and radial motion than the right. In addition, a significant difference between male and female ulnar and radial movements was found (F(1,26) = 5.48, $p<0.0272$). Females had greater ulnar and radial hand movements than did males. With regard to stage, typing random words (stage 2) had significantly higher ulnar and radial wrist deviation movements than typing random characters (stage 1) (F(1,26)=39.74, $p<0.0001$).

In terms of interactions, a significant four-way interaction (Stage x Hand x Keyboard x Gender) reached statistical significance (F(1,26) = 7.88, $p<0.0093$). For ease of interpretation, Figure 30 shows this four-way interaction as 4 two-way interactions, one for each stage x hand. Simple effects tests of the interaction at the 0.05 level of significance showed that female right hand ulnar and radial movements were significantly greater for the QWERTY keyboard group of the random word stage when compared to male ulnar and radial movements. Also significant was the ulnar and radial stage 2, females' right hand movements between the two keyboards. Females in the QWERTY group had significantly higher ulnar and radial wrist motions than their female Keybowl counterparts.

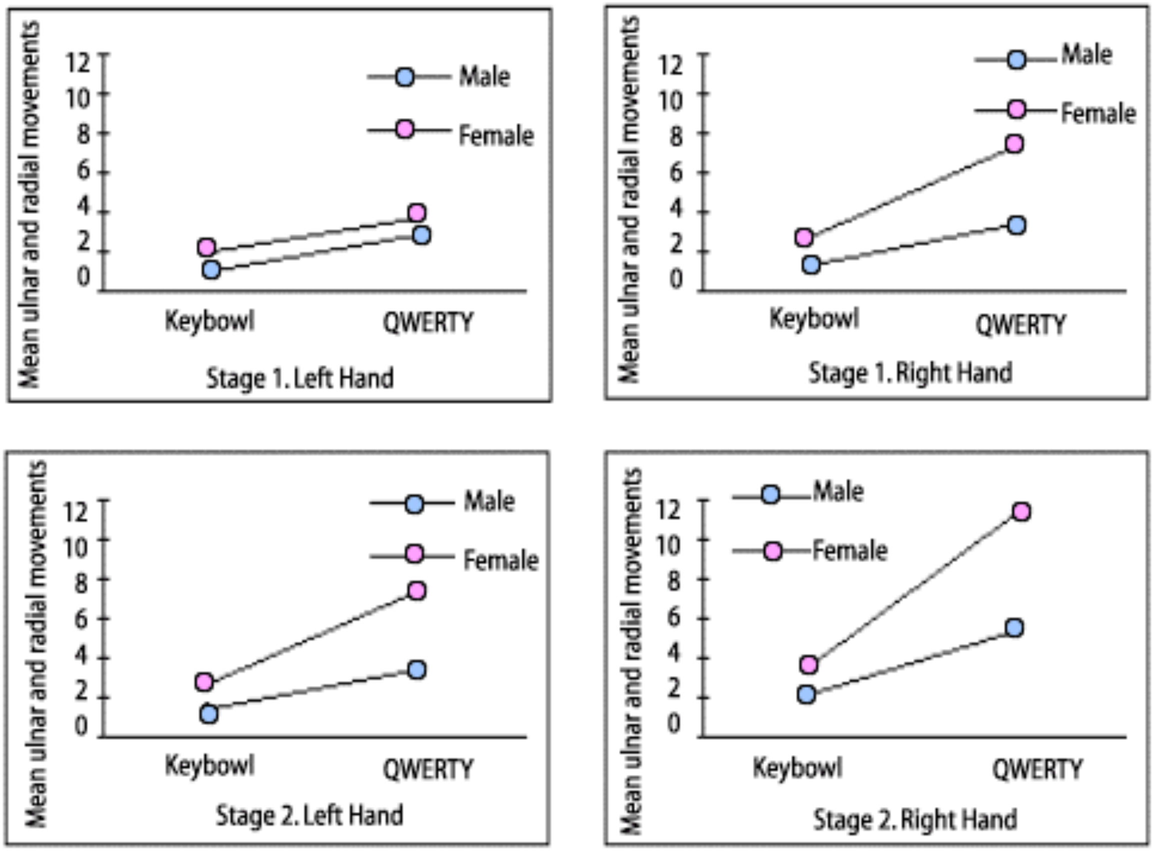


Figure 30. Mean ulnar and radial movements as a function of stage, hand, keyboard, and gender.

Performance

Several important findings were discovered regarding subject typing performance measured in gross words per minute. The data were analyzed using a repeated measures 2 x 2 x 2 x 8 mixed model analysis of variance (ANOVA). Keyboard type and gender were between subject factors whereas stage and session were the within subject factors. The dependent variable is the number of characters typed per session. A significant difference existed between the two keyboard groups; QWERTY typists outperformed Keybowl typists (F(1,26) = 47.55, p<0.0001). It was also determined that females outperformed males (F(1,26) = 4.79, p<0.0378).

The 15 Keybowl subjects had memorized (as determined by a subjective questionnaire) the locations of all 16 characters in the first 4 sessions of experimentation (1 hour 15 minutes). These subjects typed an average of 24 GWPM (s.d. =8) after using the Keybowl for 5 hours. In comparison, the 15 subjects in the QWERTY keyboard group typed an average of 46 GWPM (s.d. =11) after 5 hours. Recall that the QWERTY group typists typed an average of 42 GWPM (s.d. = 14) and the Keybowl group typed an average of 40 GWPM (s.d.=11) before the experiment. The disparity between the QWERTY keyboard users typing rate for the study and timed test rate can be attributed to the reduced character set used in the study compared to a full character set used in the one minute typing test.

The keyboard main effect was found to be significant ($\underline{F}(1,26) = 47.75$, $\underline{p}<0.0001$), with QWERTY typists typing more quickly than Keybowl typists. Gender differences were also significant ($\underline{F}(1,26) = 47.75$, $\underline{p}<0.0001$), with females typing more quickly than males. The main effect of stage was also statistically significant. Stage 2 typing performance was greater than stage 1 typing performance ($\underline{F}(1,26) = 290.92$, $\underline{p}<0.0001$). In addition, two significant three-way (Stage x Keyboard x Gender) and (Stage x Session x Keyboard) interactions were found $\underline{F}(1,26) = 11.31$, $\underline{p}<0.0024$, $\underline{F}(7,182) = 5.58$, $\underline{p}<0.0001$, respectively. The latter three-way interaction indicated that for stages 1 and 2, the QWERTY group out performed the Keybowl group in terms of gross characters/words typed. In addition, a significant difference existed within the QWERTY and Keybowl performance measures across session for each of the stages (see Figure 31). Stage x Keyboard x Gender is perhaps a more revealing interaction.

For ease of interpretation, Figure 32 shows this three-way interaction as 2 two-way interactions, one for each stage. The three-way interaction indicated that males and females were significantly different between the two keyboard groups. Simple effect tests of the interaction at the 0.05 level of significance showed that for stage 1, female and male performances between the keyboard groups were not significantly different. Stage 2 revealed a significant difference in typing performance between males and females for the QWERTY group. Females using the QWERTY typing significantly higher gross words per minute than males. No such difference existed between males and females in the Keybowl group.

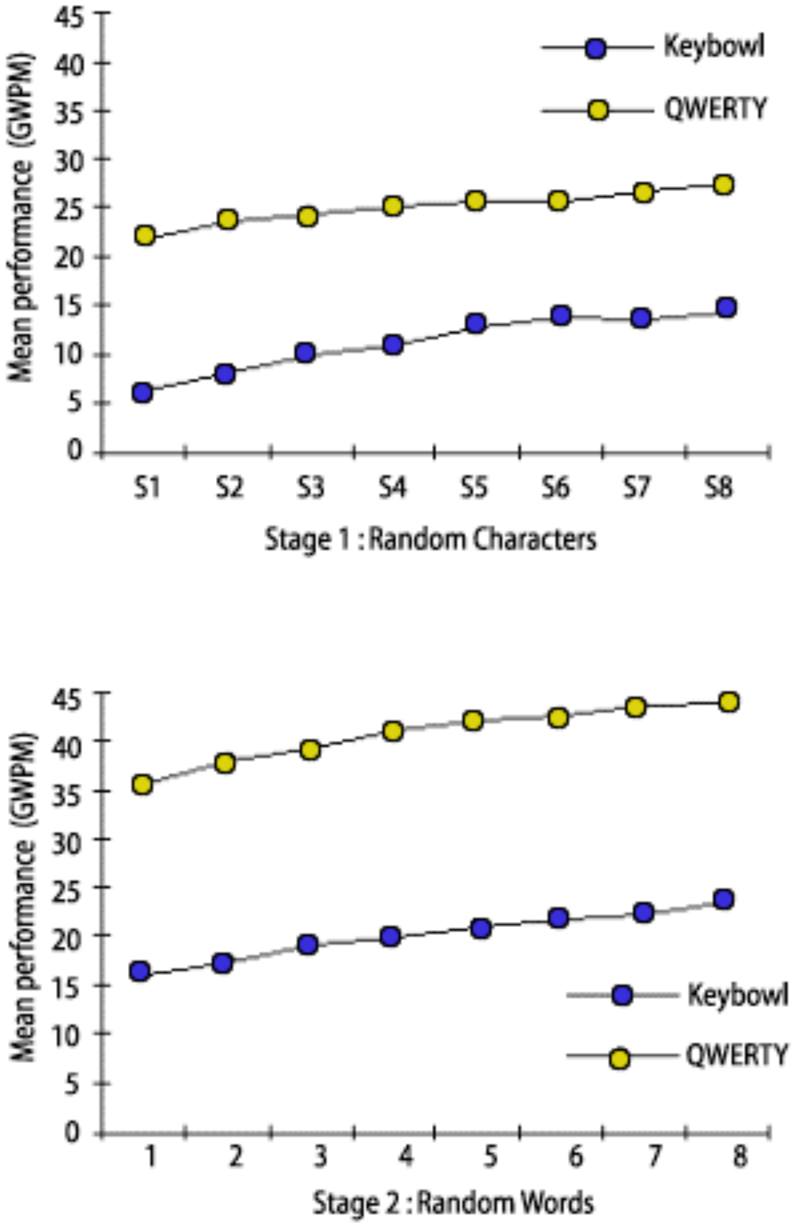


Figure 31. Mean performance as a function of stage, session, and keyboard.

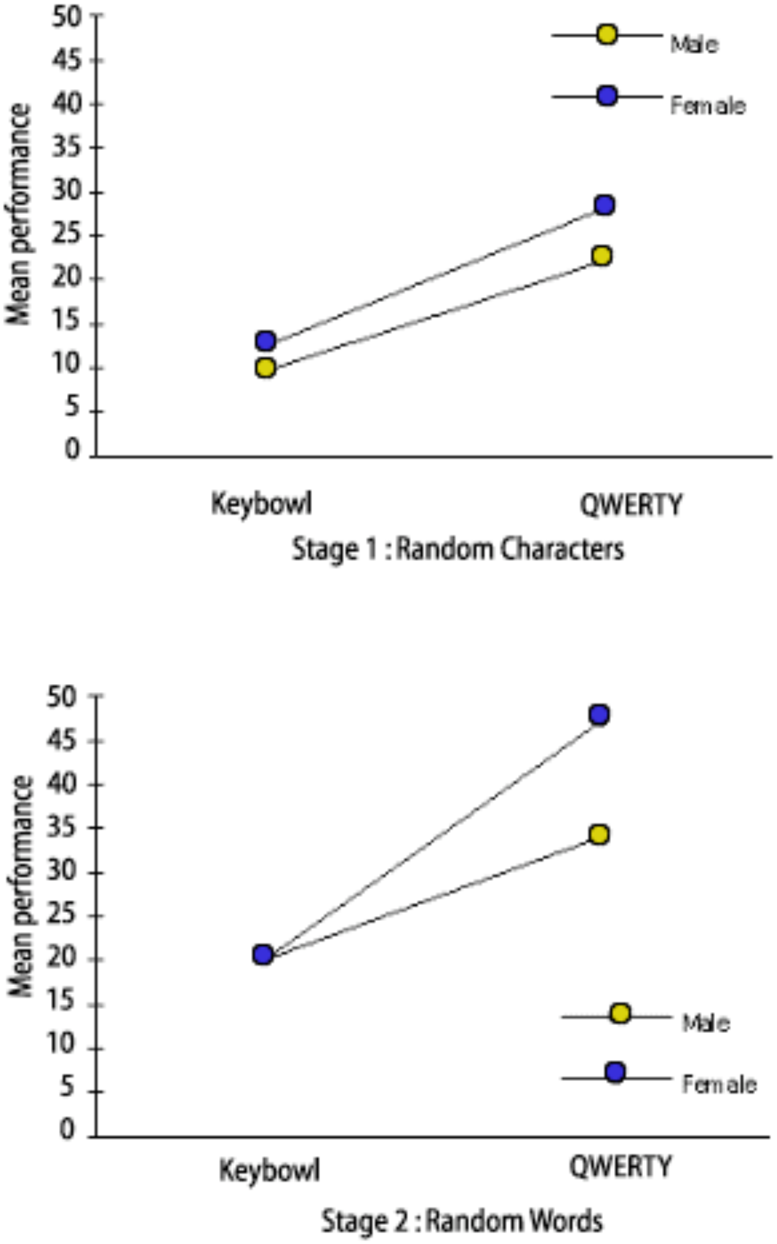


Figure 32. Mean performance as a function of stage, gender, and keyboard.

Wrist Movement as a Function of Typing Performance. Wrist motion may increase or decrease as a function of typing speed. No studies were found to substantiate or reject the notion of typing speed as an indicator of wrist motion. As stated previously, the QWERTY keyboard group had significantly higher wrist movement and typing speeds than the Keybowl group. Could it be that as the speed of typing increases, wrist movement increases? If such a supposition holds true then maybe the Keybowl wrist movements are a function of slower typing speeds obtained, not an ergonomic advantage. An equal comparison between the two groups was therefore performed to determine if the typing speed is a main contributor to wrist movement between the two keyboard groups. The two keyboard groups were analyzed such that typing speeds in the random word session were not significantly different ($\underline{F}(1,20) = 3.42$, $\underline{p}<0.079$). This was performed by taking the 11 fastest Keybowl typists GWPM sessions and finding a comparable 11 QWERTY keyboard typists sessions for comparison. Once identified, the wrist movement data were analyzed to determine if a significant difference existed between the two groups. Significant differences were still found in the flexion/extension movements of the left and right hands ($\underline{F}(1,20) = 12.73$, $\underline{p}<0.0019$); ($\underline{F}(1,20) = 5.58$, $\underline{p}<0.00046$) respectively. There were also significant differences found in the ulnar/radial movements of the left and right hands ($\underline{F}(1,20) = 8.99$, $\underline{p}<0.007$); ($\underline{F}(1,20) = 9.37$, $\underline{p}<0.006$) respectively. It is therefore believed that some other factor, such as a better ergonomic design, is responsible for the decrease in wrist motion of the Keybowl typists over the QWERTY keyboard typists.

Learning Rates

The Keybowl and QWERTY keyboard learning rates were analyzed in terms of their respective random character and random word sessions. Learning rates were calculated using a log linear model proposed by Hancock and Bayha (1982). The analysis consisted of doubling the output and computing the word per cycle increase. Total typing time for each group of sessions analyzed was 2.5

hours (i.e., subjects typed 2.5 hours of random characters and 2.5 hours or random words). For sessions 1 through 8, the random character sessions, a 75% uniform improvement rate was found. The range of values was 6.30 GWPM in session 1 to 15.20 GWPM in session 8. Given the uniform level of improvement, the time to reach an adequate level of typing proficiency, 60 GWPM for example, was computed to be 70 hours. A similar procedure was used to compute the improvement rate for sessions 9-16; typists had an 85% improvement rate for sessions 9-16, the random word sessions. Typing performances ranged from 16.26 GWPM in session 9 to 23.50 GWPM in session 16. With an 85% improvement rate, 60 GWPM could be attained with 140 hours of training.

The QWERTY keyboard group had a 93% improvement rate for both random character and random word sessions. Sessions 1-8, the random character sessions, had a range of 22.4 GWPM in session 1 to 28.14 GWPM in session 8. The time to reach 60 GWPM was projected to be 3,612 hours. Sessions 9-16, the random word sessions, had a range of 36.88 GWPM in session 9 to 45.55 GWPM in session 16. The time to reach 60 GWPM was projected to be 36 hours.

The data, as plotted in Figure 33, indicate that after 5 hours of training, Keybowl typists were typing at the same speed as session 2 QWERTY typists. Within the group, typists attained an average of 60% (s.d. 14%) of their QWERTY typing speed after only 5 hours of using the Keybowl.

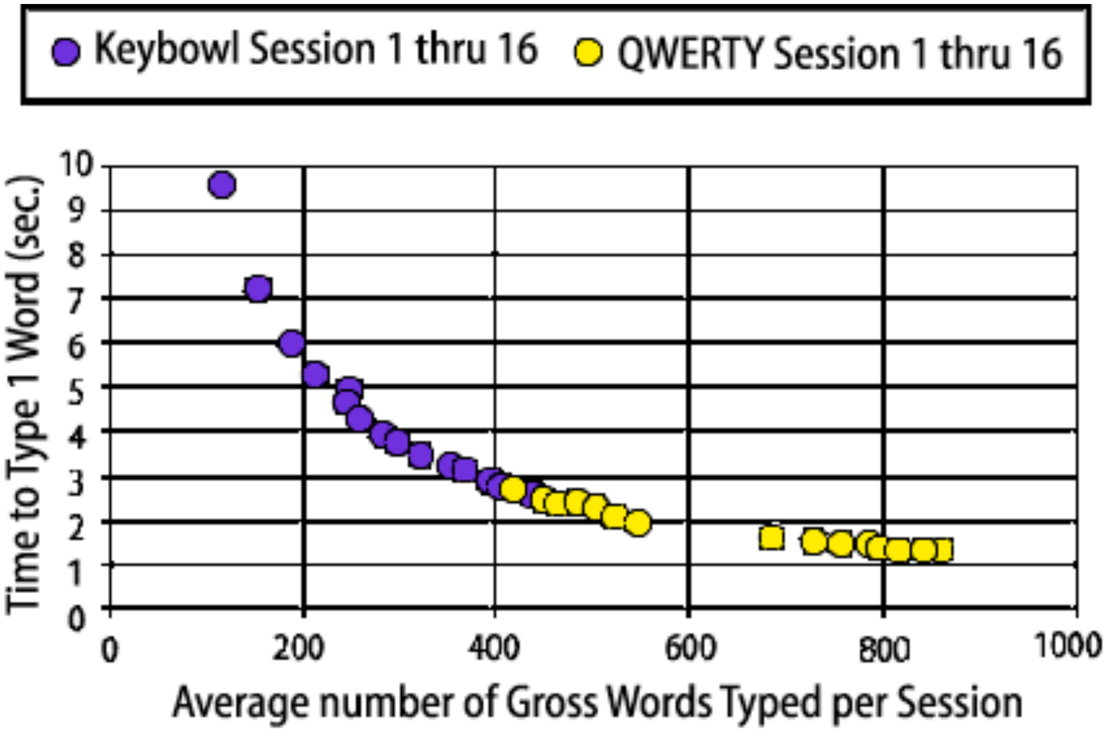


Figure 33. Keybowl and QWERTY keyboard improvement curves.

Subjective Workload (NASA-TLX) Results

The NASA Task Load Index (TLX) measured subjective workload. The TLX data were analyzed using a repeated measures 2 x 2 x 2 x 8 mixed model analysis of variance (ANOVA). Keyboard type and gender were between subject factors whereas stage and session were the within subject factors.

The main effects of Stage and Session were found to be statistically significant F(1,26) = 18.82, p<0.0005, F(7,182) = 12.13, p<0.0001, respectively. The random character stage had a higher level of perceived workload than the random word stage. Analysis of range tests on the session main effect reveled that sessions 1, 5, and 7 had the highest perceived workloads. In addition, a significant three-way (Session x Keyboard x Gender) interaction was found

(F(7,182) = 2.67, $p<0.0117$). For ease of interpretation, Figure 34 (Tables 6 and 7) shows this three-way interaction as 2 two-way interactions, one for each gender. The three-way interaction indicated that for males, Keybowl and QWERTY subjective workload measures were significantly different for session 5. Males using the Keybowl indicated that they had a higher perceived workload for session 5 than did their male QWERTY counterparts. For the females, sessions 1, 2, 3, 4, and 5 were significantly different between the two keyboards. Females using the Keybowl indicated that they had a higher perceived workload than their QWERTY counterparts. It was also found that workload was different between the sessions for each keyboard.

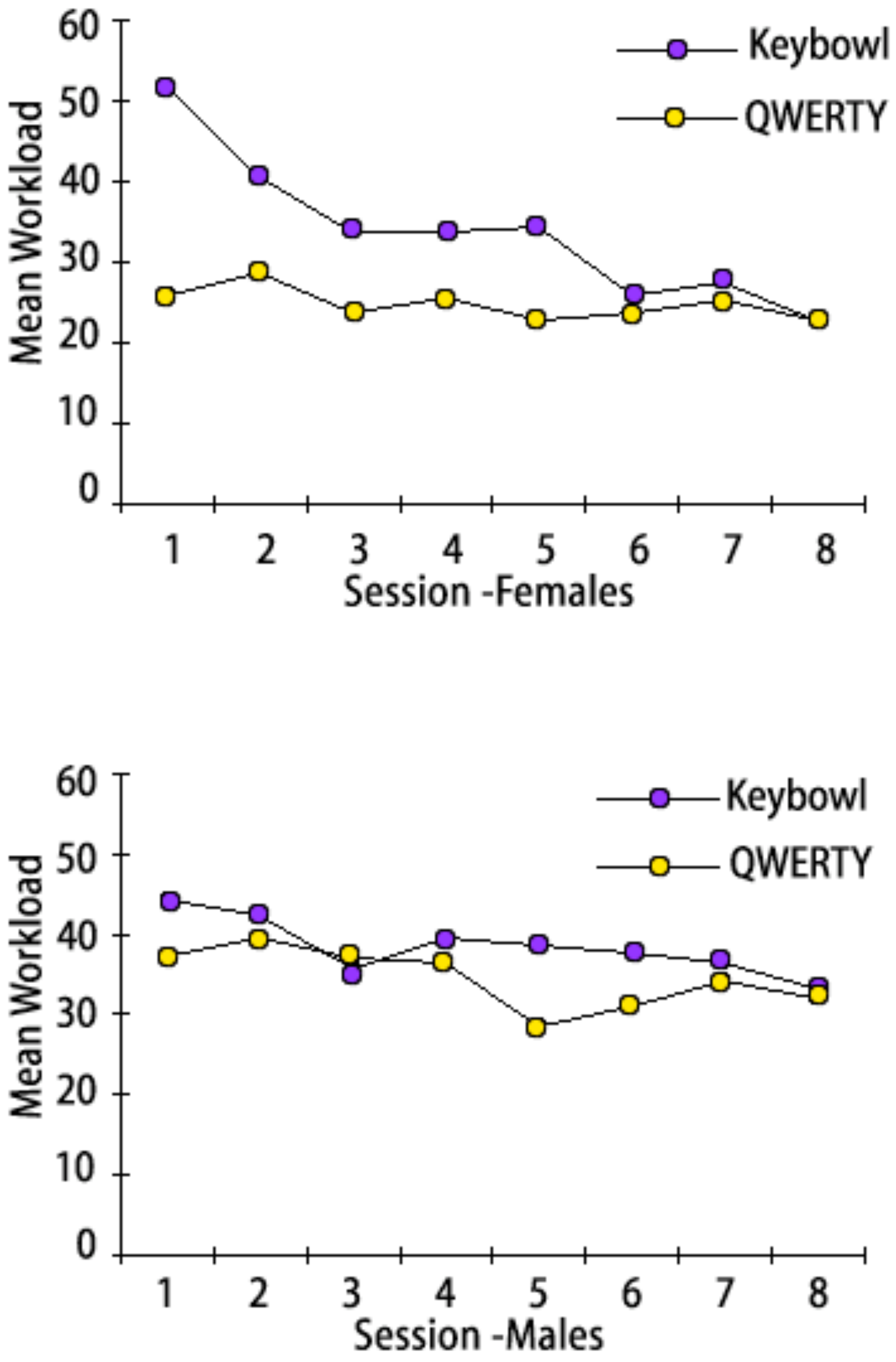


Figure 34. Mean workload as a function of session, keyboard, and gender. Table 6.

Tests of simple effects of session x keyboard for males

Source	DF	SS	MS	F	P
Keyboard at One	1	1102.771	1102.771	2.789	>0.05*
Keyboard at Two	1	187.591	187.591	.475	>0.05*
Keyboard at Three	1	41.916	41.916	.106	>0.05*
Keyboard at Four	1	187.58	187.58	.474	>0.05*
Keyboard at Five	1	2157.687	2157.687	5.458	<0.0275*
Keyboard at Six 1	993.491	993.491	2.513	>0.05*	
Keyboard at Seven	1	100.128	100.128	.253	>0.05*
Keyboard at Eight	1	43.119	43.119	.109	>0.05*
Session at Keybowl	7	3967.605	566.801	7.353	<0.0001
Session at QWERTY	7	4242.434	606.062	7.862	<0.0001

*Satterthwaite MSE = 395.336
*Satterthwaite DF (DEN) 37.571

Table 7.

Tests of simple effects of session x keyboard for females

Source	DF	SS	MS	F	P
Keyboard at One	1	25455.96	25455.96	64.391	<0.0001*
Keyboard at Two	1	5625.058	5625.058	14.229	<0.0006*
Keyboard at Three	1	3838.102	3838.102	9.708	<0.0040*
Keyboard at Four	1	2495.578	2495.578	6.313	<0.0173*
Keyboard at Five	1	5236.467	5236.467	13.246	<0.0009*
Keyboard at Six 1	169.618	169.618	.429	>0.05*	
Keyboard at Seven	1	174.117	174.117	.440	>0.05*
Keyboard at Eight	1	.547	.547	.001	>0.05*
Session at Keybowl	7	45117.43	6445.347	83.61	<0.0001
Session at QWERTY	7	2138.762	305.537	3.963	<0.0005

*Satterthwaite MSE = 395.336
*Satterthwaite DF (DEN) 37.571

Questionnaire Analysis

Two identical questionnaires were administered, one after each stage of testing. Correlation analysis was performed between questionnaire 1, the random character questionnaire, and questionnaire 2, the random word questionnaire. Correlation's between responses to questions averaged 0.962 with a standard deviation of 0.053. Correlation analysis was also performed on the aggregate questionnaire data to determine if questions could be grouped according to more general measures. The questions that had a similar response patterns were lumped together as a composite variable. This analysis determined which groups of questions have high correlation's. The 21 question questionnaire reduced to 7 composite variables, they include: 1) Performance, 2) Meaningfulness, 3) Ease of use, 4) Personal Satisfaction, 5) Importance of typing task, 6) Major fatigue components, and 7) Minor fatigue components. A Kolmogorov-Smirnov non-parametric test was performed to determine if any significant differences existed between the two keyboard groups across each one of the variables. Ease of use and major fatigue factors were the only two factors that were significantly different between the two keyboard groups ($p< 0.009$ and $p< 0.003$, respectively).

Error Analysis

The data were analyzed using a repeated measures 2 x 2 x 2 x 4 x 16 mixed model analysis of variance (ANOVA). Keyboard type and gender were between subject factors whereas stage, session group, and letter were the within subject factors, respectively. The dependent variable was the number of typing errors per session. Session groups were comprised of 4 sessions (e.g., session group 1 was comprised of sessions 1 through 4, session group 2 was comprised of session 4 through 8, etc.). Before the error analysis was performed, a definition of what constituted an error needed to be provided. In this study, errors were computed on a per character basis; any single character, whether it be a random character session or random word session, that did not match the character to be typed was considered an error. The other error types, which were not part of this study, are insertion, omission, substitution, transposition, and other (Cooper, 1983). Using the per character basis, Keybowl typists had an accuracy level of 82% (s.d. 5.47) whereas keyboard typists had an accuracy level of 97% (s.d. 3.06). The QWERTY keyboard had significantly less errors than the Keybowl ($F(1,26) = 10.13$, $p<0.0040$). With regard to the Stage main effect, typing random words had significantly higher typing errors than typing random characters ($F(1,26) = 14.15$, $p<0.0010$). The session group effect had a similar effect. The last four sessions of each stage had significantly higher typing errors than the first four sessions ($F(1,26) = 16.87$, $p<0.0005$). Lastly, the main effect of Letter was statistically significant ($F(15,390) = 4.46$, $p<0.0001$). The characters "c" and "i" had the highest errors whereas the letters "p" and "m" the lowest.

In analyzing the number of characters typed to number of errors, the proportion was the same between the stages for the QWERTY keyboard group (i.e., 97% accuracy in stage 1 and stage 2) and slightly higher accuracy occured for the Keybowl in stage 2 (i.e., 81% accuracy in stage 1, 84% accuracy in stage2). A two-way interaction of session group and keyboard existed ($F(1,26) = 6.48$, $p<0.0172$). A test of simple effects indicated that QWERTY typists had significantly higher error rates in the random word stage compared to the random character stage. No such effect was found for the Keybowl group. A two-way interaction of letter and keyboard existed ($F(15,390) = 5.02$, $p<0.0001$). A test of simple effects indicated that characters A, E, R, T, F, D, C, S, U, I, O, L , and H were significantly different between the two keyboards. The only characters that were not significantly different were P, M, and N. The proportion of errors by letter were similar for each of the hands (see Figure 35) but the left hand had a significantly greater number of errors than the right (as demonstrated by the ANOVA).

A three-way interaction (Stage x Letter x Keyboard) was also found to be significant ($F(15,390) = 4.73$, $p<0.0001$). In stage 1, the random character stage, characters A, T, D, C, S, U, O, L, H were significantly higher $F(1,390) = 5.697$, $p<0.0225$, $F(1,390) = 6.843$, $p<0.0125$, $F(1,390) = 4.935$, $p<0.0330$, $F(1,390) = 39.67$, $p<0.0001$, $F(1,390) = 10.591$, $p<0.0025$, $F(1,390) = 7.574$, $p<0.0090$, $F(1,390) = 5.064$, $p<0.0305$, $F(1,390) = 7.846$, $p<0.0080$, and $F(1,390) = 8.443$, $p<0.0060$, repectively, in the Keybowl group whereas characters E, R, F, I, P, M, and N were not significantly different. In stage 2, the random word stage, characters A, E, R, T, F, C, U, I, L, and H were significantly higher in the Keybowl group $F(1,390) = 10$, $p<0.0030$, $F(1,390) = 21.39$, $p<0.0001$, $F(1,390) = 19.89$, $p<0.0001$, $F(1,390) = 23.54$, $p<0.0001$, $F(1,390) = 15.32$, $p<0.0005$, $F(1,390) = 34.75$, $p<0.0001$, $F(1,390) = 18.364$, $p<0.0001$, $F(1,390) = 13.51$, $p<0.0010$, $F(1,390) = 48.23$, $p<0.0001$, and $F(1,390) = 18.84$, $p<0.0001$, repectively. Characters D, S, O, P, M, and N were not significantly different (see Figure 36).

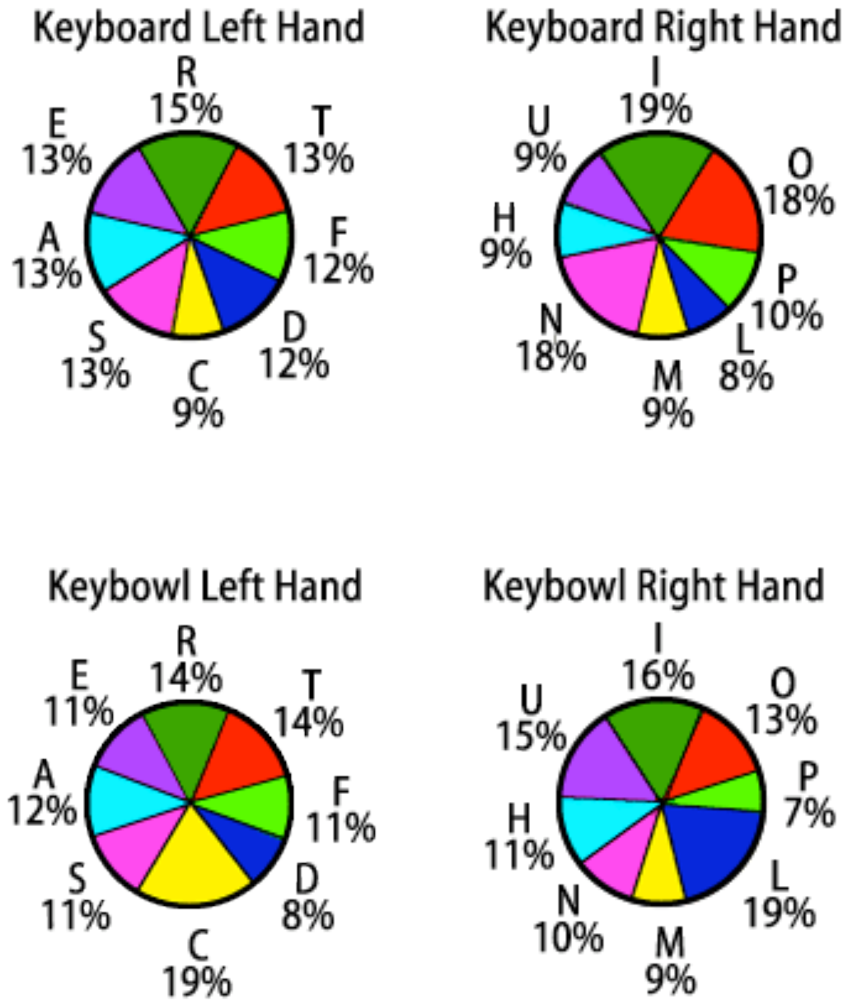
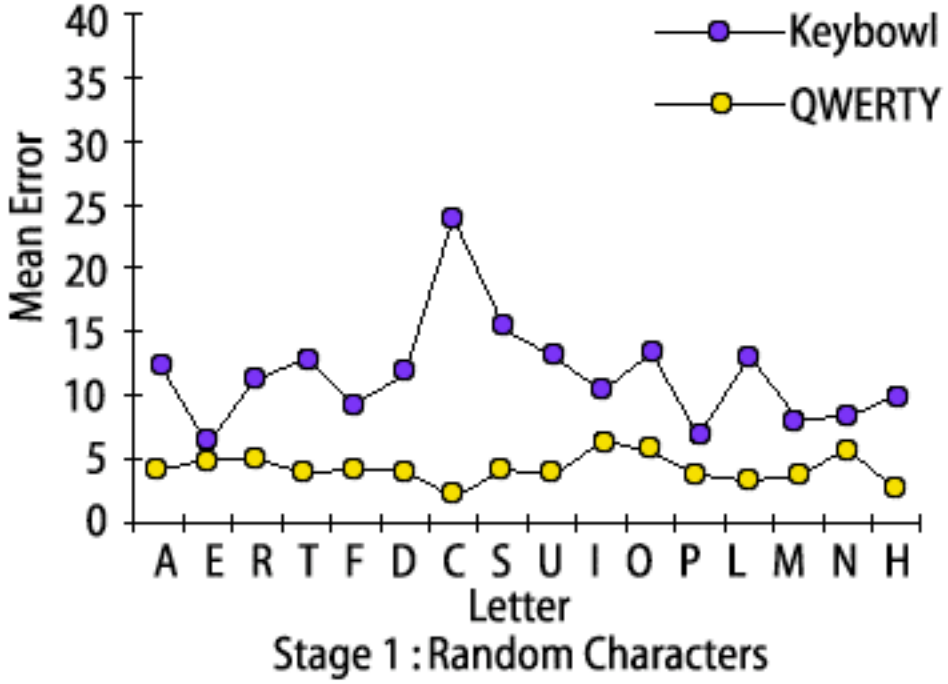


Figure 35. Percentage of errors per character location per hand per keyboard.

The three-way interaction (Stage x Session group x Letter) was also found to be significant (F(15,390) = 3.00, p<0.0001). In stage 1, the random character stage, characters A, F, D, C, S, U, P, L, N, and H were significantly higher in session group 1 (sessions 1 through 4) when compared to session group 2 (sessions 5 through 8) F(1,390) = 10.55, p<0.0015, F(1,390) = 23.84, p<0.0001, F(1,390) = 13.032, p<0.0005, F(1,390) = 42.2, p<0.0001, F(1,390) = 18.865, p<0.0001, F(1,390) = 4.705, p<0.0310, F(1,390) = 15.013, p<0.0001, F(1,390) = 6.586, p<0.0110, and $F(1,390) = 40.26$, $p<0.0001$, repectively. Characters E, R, T, U, I, O, and M were not significantly different. In stage 2, the random word stage, characters A, E, R, T, U, O, P, N, and H were significantly higher in session group 1 (sessions 9 through 12) when compared to session group 2 (sessions 13 through 16) $F(1,390) = 5.023$, $p<0.0260$, $F(1,390) = 68.62$, $p<0.0001$, $F(1,390) = 18.734$, $p<0.0001$, $F(1,390) = 21.266$, $p<0.0001$, $F(1,390) = 39.973$, $p<0.0001$, $F(1,390) = 4.95$, $p<0.0270$, $F(1,390) = 7.692$, $p<0.0060$, and $F(1,390) = 110.372$, $p<0.0001$, repectively. Characters F, D, C, S, I, L, and M were not significantly different (see Figure 37).



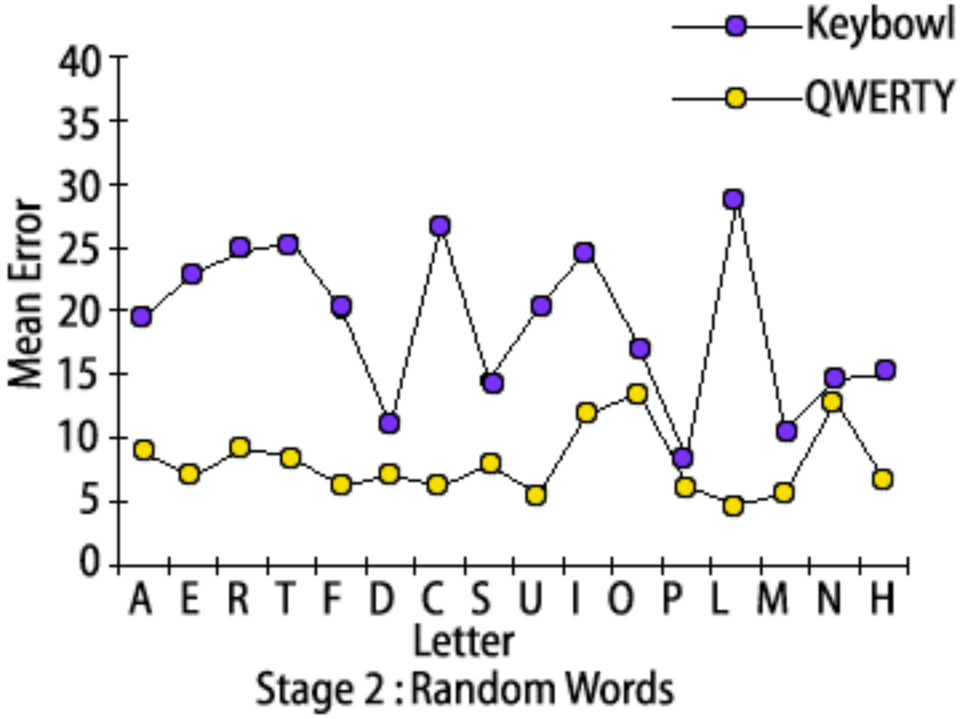
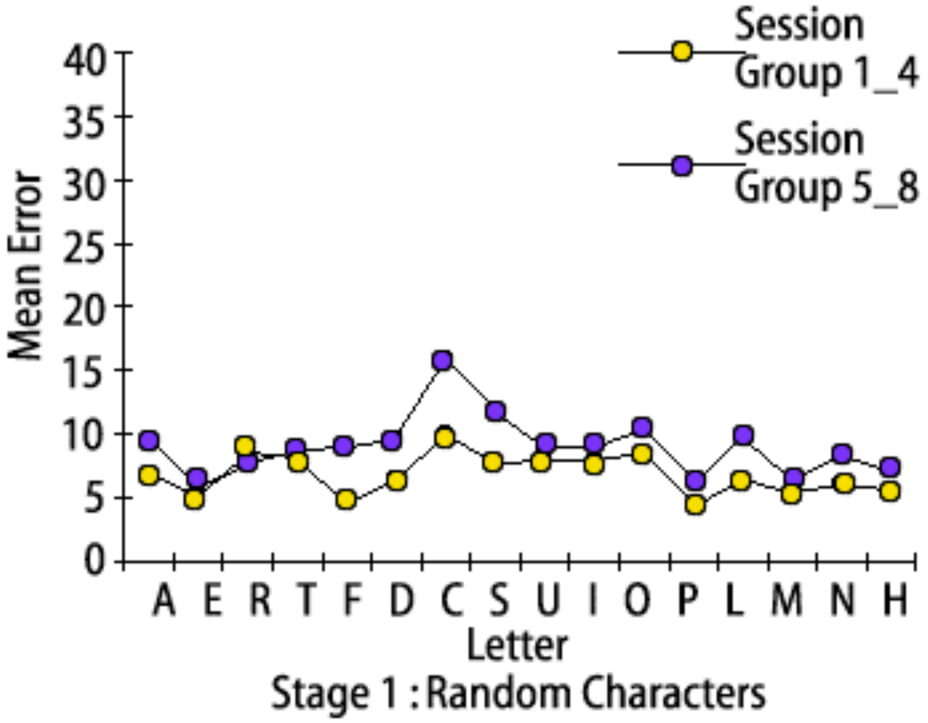


Figure 36. Mean error as a function of stage, letter, and keyboard.



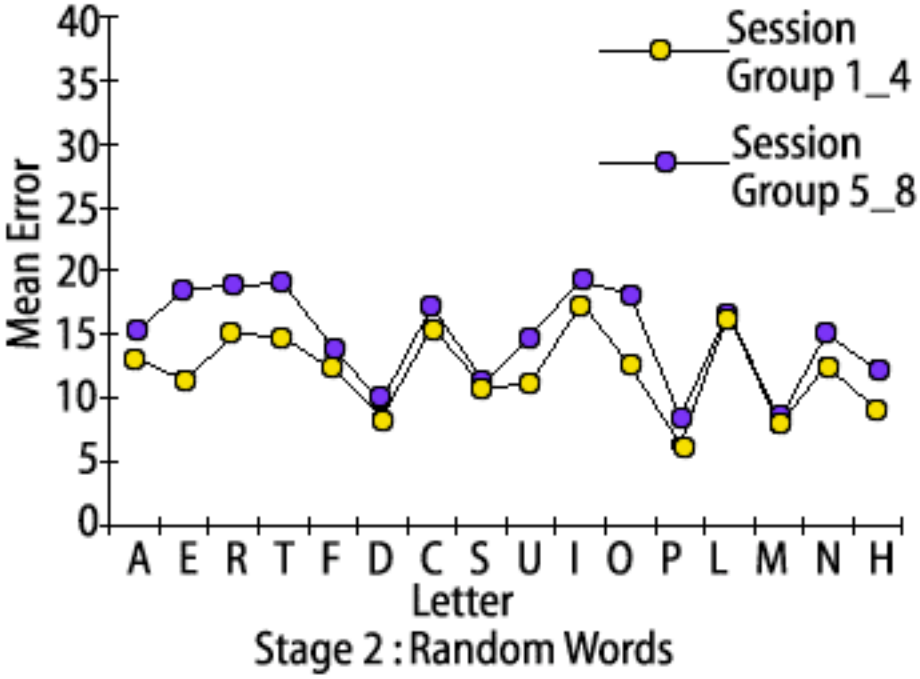


Figure 37. Mean error as a function of stage, session group, and letter.

Typing Errors in Relation to Right and Left Hands

When hand was substitued for stage, a four-way interaction (Session group x Hand x Letter x Keyboard) was found to be statistically significant $\underline{F}(21,546) = 2.50$, $\underline{p}<0.0003$. The four-way interaction is interpreted as 8 two-way interactions, one for each session group x hand (see Figure 38 in conjunction with Tables 8, 9, 10, 11, 12, 13, 14 and 15). The four-way interaction indicated the left hand characters in session group 1 (sessions 1 through 4), characters A, R, T, C, and S, were significantly different between the two keyboards. Characters E, F, and D were not significantly different. The number of errors for each character within each one of the keyboard groups was also significantly different. The right hand characters in session group 1 (sessions 1 through 4), characters H, U, O, and L , were significantly different between the two keyboards. Characters I, P, M and N were not significantly different. The number of errors for each character within each one of the keyboard groups was also significantly different. The left hand characters in session group 2 (sessions 5 through 8), characters A, R, T, F, D, C, and S, were significantly different between the two keyboards. Character E was not significantly different. The number of errors for each character within the Keybowl group was also significantly different, no difference was found between QWERTY characters. Right hand characters in session group 2 (sessions 5 through 8), characters H, U, I, O, L, and N, were significantly different between the two keyboards. Characters P and M were not significantly different. The number of errors for each character within the group was also significantly different. The left hand characters in session group 3 (sessions 9 through 12), characters A, E, R, T, F, C, and S, were significantly different between the two keyboards. Character D was not significantly different. The number of errors for each character within each one of the keyboard groups was also significantly different. Right hand characters in session group 3 (sessions 9 through 12), characters H, U, I, and L were significantly different between the two keyboards; characters O, P, M, and N were not. The number of errors for each character within each one of the keyboard groups was also significantly different. The left hand characters in session group 4 (sessions 13 through 16), characters A, E, R, T, F, and C, were significantly different between the two keyboards; characters D and S were not. The number of errors for each character within each one of the keyboard groups was also significantly different. The right hand characters in session group 4 (sessions 13 through 16), characters H, U, I, O, L, were significantly different between the two keyboards whereas characters P, D, and C were not. The number of errors for each character within each one of the keyboard groups was also significantly different.

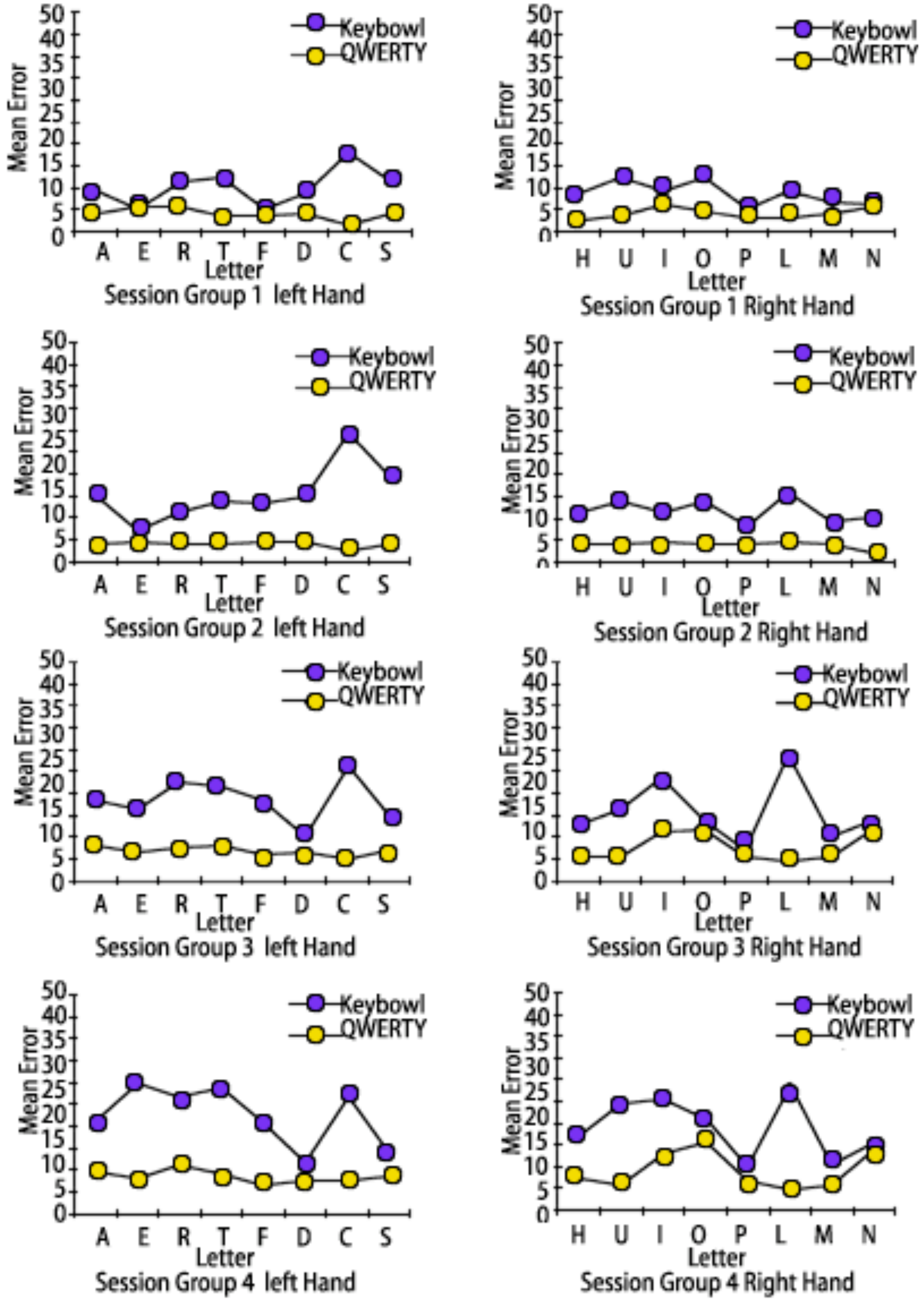


Figure 38. Mean error as a function of session group, hand, letter, and keyboard.

Table 8.

Tests of simple effects of keyboard x letter interaction for Session group 1, Left Hand

Source	DF	SS	MS	F	P
Keyboard at A	1	874.8	874.8	4.349	<0.0445*
Keyboard at E	1	10.8	10.8	.054	>0.05*
Keyboard at R	1	858.675	858.675	4.269	<0.0465*
Keyboard at T	1	2193.076	2193.076	10.903	<0.0022*
Keyboard at F	1	81.675	81.675	.406	>0.05*
Keyboard at D	1	662.7	662.7	3.295	>0.05*
Keyboard at C	1	8167.5	8167.5	40.606	<0.0001*
Keyboard at S	1	1620.675	1620.675	8.058	<0.0075*
Letter at Keybowl	7	7513.198	1073.314	31.095	<0.0001
Letter at QWERTY	7	657.526	93.932	2.721	<0.0088

*Satterthwaite MSE = 201.138
*Satterthwaite DF (DEN) 37.117

Table 9.

Tests of simple effects of keyboard x letter interaction for Session group 1, Right Hand

Source	DF	SS	MS	F	P
Keyboard at U	1	2403.075	2403.075	11.947	<0.0015*
Keyboard at I	1	309.123	309.123	1.537	>0.05*
Keyboard at O	1	1877.042	1877.042	9.332	<0.0045*
Keyboard at P	1	96.123	96.123	.478	>0.05*
Keyboard at L	1	1221.132	1221.132	6.071	<0.0190*
Keyboard at M	1	223.587	223.587	1.112	>0.05*
Keyboard at N	1	27.075	27.075	.135	>0.05*
Keyboard at H	1	1263.604	1263.604	6.282	<0.0170*
Letter at Keybowl	7	3126.577	446.654	12.94	<0.0001
Letter at QWERTY	7	742.006	106.001	3.071	<0.0035

*Satterthwaite MSE = 201.138
*Satterthwaite DF (DEN) 37.117

Table 10.

Tests of simple effects of keyboard x letter interaction for Session group 2, Left Hand

Source	DF	SS	MS	F	P
Keyboard at A	1	3663.074	3663.074	18.212	<0.0001*
Keyboard at E	1	235.199	235.199	1.169	>0.05*
Keyboard at R	1	1576.875	1576.875	7.84	<0.0085*
Keyboard at T	1	2707.5	2707.5	13.461	<0.0010*
Keyboard at F	1	2296.875	2296.875	11.419	<0.0020*
Keyboard at D	1	3402.676	3402.676	16.917	<0.0005*
Keyboard at C	1	21870.0	21870.0	108.731	<0.0001*
Keyboard at S	1	6840.298	6840.298	34.008	<0.0001*
Letter at Keybowl	7	17964.54	2566.363	74.35	<0.0001
Letter at QWERTY	7	208.499	29.786	.863	>0.05

*Satterthwaite MSE = 201.138
*Satterthwaite DF (DEN) 37.117

Table 11.

Tests of simple effects of keyboard x letter interaction for Session group 2, Right Hand

Source	DF	SS	MS	F	P
Keyboard at U	1	2916.589	2916.589	14.5	<0.0005*
Keyboard at I	1	1474.204	1474.204	7.329	<0.0105*
Keyboard at O	1	3054.243	3054.243	15.185	<0.0005*
Keyboard at P	1	529.20	529.20	2.631	>0.05*
Keyboard at L	1	4099.684	4099.684	20.382	<0.0001*
Keyboard at M	1	820.587	820.587	4.080	>0.05*
Keyboard at N	1	1867.562	1867.562	9.285	<0.0045*
Keyboard at H	1	1529.338	1529.338	7.604	<0.0095*
Letter at Keybowl	7	3099.529	442.79	12.828	<0.0001
Letter at QWERTY	7	205.98	29.426	.852	>0.05

*Satterthwaite MSE = 201.138
*Satterthwaite DF (DEN) 37.117

Table 12.

Tests of simple effects of keyboard x letter interaction for Session group 3, Left Hand

Source	DF	SS	MS	F	P

Keyboard at A	1	3151.875	3151.875	15.67	<0.0005*
Keyboard at E	1	3121.201	3121.201	15.518	<0.0005*
Keyboard at R	1	7022.703	7022.703	34.915	<0.0001*
Keyboard at T	1	5467.502	5467.502	27.183	<0.0001*
Keyboard at F	1	4650.073	4650.073	23.119	<0.0001*
Keyboard at D	1	388.801	388.801	1.933	>0.05*
Keyboard at C	1	13932.070	13932.070	69.266	<0.0001*
Keyboard at S	1	1825.202	1825.202	9.074	<0.0050*
Letter at Keybowl	7	10556.530	1508.075	43.69	<0.0001
Letter at QWERTY	7	529.73	75.676	2.192	<0.0335

*Satterthwaite MSE = 201.138
*Satterthwaite DF (DEN) 37.117

Table 13.

Tests of simple effects of keyboard x letter interaction for Session group 3, Right Hand

Source	DF	SS	MS	F	P
Keyboard at U	1	3525.169	3525.169	17.526	<0.0005*
Keyboard at I	1	4915.206	4915.206	24.437	<0.0001*
Keyboard at O	1	97.198	97.198	.483	>0.05*
Keyboard at P	1	47.628	47.628	.237	>0.05*
Keyboard at L	1	17802.29	17802.29	88.508	<0.0001*
Keyboard at M	1	765.075	765.075	3.804	>0.05*
Keyboard at N	1	145.199	145.199	.722	>0.05*
Keyboard at H	1	1537.968	1537.968	7.646	<0.0089*
Letter at Keybowl	7	21606.82	3086.688	89.424	<0.0001
Letter at QWERTY	7	4145.662	592.237	17.158	<0.0001

*Satterthwaite MSE = 201.138
*Satterthwaite DF (DEN) 37.117

Table 14.

Tests of simple effects of keyboard x letter interaction for Session group 4, Left Hand

Source	DF	SS	MS	F	P
Keyboard at A	1	4002.076	4002.076	19.897	<0.0001*

Keyboard at E	1	14061.670	14061.670	69.911	<0.0001*
Keyboard at R	1	7300.803	7300.803	36.297	<0.0001*
Keyboard at T	1	12000	12000	59.66	<0.0001*
Keyboard at F	1	6307.5	6307.5	31.359	<0.0001*
Keyboard at D	1	541.875	541.875	2.694	>0.05*
Keyboard at C	1	10944.29	10944.29	54.412	<0.0001*
Keyboard at S	1	811.201	811.201	4.033	>0.05*
Letter at Keybowl	7	19294.34	2756.334	79.854	<0.0001
Letter at QWERTY	7	792.898	113.271	3.282	<0.0020

*Satterthwaite MSE = 201.138
*Satterthwaite DF (DEN) 37.117

Table 15.
Tests of simple effects of keyboard x letter interaction for Session group 4, Right Hand

Source	DF	SS	MS	F	P
Keyboard at U	1	10513.15	10513.15	52.268	<0.0001*
Keyboard at I	1	4725.077	4725.077	23.492	<0.0001*
Keyboard at O	1	842.699	842.699	4.190	<0.0485*
Keyboard at P	1	293.906	293.906	1.461	>0.05*
Keyboard at L	1	16652.21	16652.21	82.79	<0.0001*
Keyboard at M	1	674.028	674.028	3.351	>0.05*
Keyboard at N	1	72.072	72.072	.358	>0.05*
Keyboard at H	1	2782.108	2782.108	13.832	<0.0010*
Letter at Keybowl	7	20030.13	2861.447	82.899	<0.0001
Letter at QWERTY	7	7854.804	1122.115	32.509	<0.0001

*Satterthwaite MSE = 201.138
*Satterthwaite DF (DEN) 37.117

Discussion

The results of this study support the research notion that the Keybowl has the potential to become an effective alternative device for typing with respect to the areas evaluated: 1) ergonomic considerations. The results of this study support the research hypothesis that the Keybowl's flexion & extension and ulnar & radial wrist movements are significantly less than those of the QWERTY keyboard 2) typing performance. The results of this study support the research hypothesis that the QWERTY typists typed significantly faster than typists using the Keybowl after five hours of testing 3) workload, 4) learning, and 5) subjective evaluation.

General

The objective of this study was to determine how the Keybowl compared to the QWERTY keyboard in terms of several ergonomic and performance aspects. These two metrics are very difficult to separate when evaluating a keyboard. In analyzing ergonomic aspects, a keyboard evaluation is typically done in relation to a speed metric. Typing performance analysis or ergonomic analysis performed independently of one another can be very misleading. A keyboard that demonstrates higher performance capability is not necessarily more ergonomically efficient. In fact, just the opposite is often the case. As such, it was decided that any ergonomic advantage would have to be tied to some performance metric to provide for a complete, well balanced evaluation.

The Keybowl prototype used in this study did not use chording as its principle key actuation mechanism. Because of this, the performance measures need to evaluated accordingly. Subjects typed an average 60% of their regular QWERTY typing speed after 5 hours of using the Keybowl. The chord method of key actuation may require longer periods of time to achieve the same level of proficiency. This is due to the dual bowl movements, biomechanical coordination, and learning required to type using the chordal method of key actuation. Further investigation is needed to determine learning rates for Keybowl chord actuation.

Even though chord manipulation was not implemented in this study, the obtained results are useful in analyzing a chord coding scheme. The results of this study provide insight into the relative difficulty of the chord combination through the analysis of character error actuation (discussed earlier). The character(s) with the highest error rate(s) may highly correlate to the most difficult chord combinations. In addition to the number of errors, the time between character activations can also be analyzed to determine which chord combinations will maximize character throughput. Both of these concepts should be investigated in a future study (see Callaghan, 1989, 1991).

The exact movements of chordal typing were modeled. The same movements subjects made in typing with the Keybowl prototype are the same movements that will be incorporated into the chordal design. Actual chord typing may be a little slower than rates observed in this study, but it is expected that speeds will eventually match speeds equivalent to the ones found in this study. The Keybowl typing performances found in this study were based on a QWERTY equivalent in terms of key force and displacement. The newly developed Keybowl will be optimized according to bowl displacement and force (not necessarily 4 mm of displacement and 0.7 N of force as in the QWERTY), will have a guidance system, better tactile response, and will make available different size domes to accommodate any user. It is hoped that the lower force and displacement characteristics will offset any performance decrements of chordal typing.

No serious discomfort or serious muscle fatigue were expected to be encountered by subjects at any stage during experimentation. Realistically, subjects were expected to find the Keybowl to be comfortable to a little uncomfortable. The subjects were expected to feel only slight discomfort in the wrist caused by the re-training of certain muscles to perform the typing task.

This finding, however, never materialized. The subjects gave an extremely favorable rating to the Keybowl in terms of its use, comfort, and application.

Subject groups

For both keyboards, variability between-subjects was prevalent (i.e., within each group typing speeds and wrist motions differed between subjects). This conclusion is supported by several similar studies (Conrad & Longman, 1965; Fathallah, 1988). For the QWERTY keyboard, variability can be attributed to the fact that some subjects were more familiar with the keyboard before participating in the experiment; the average usage of computers/typewriters per week may have varied between subjects. The Keybowl typing performance variability in the number of sessions cannot be totally explained by the between-subjects variability with regard to prior familiarity with computers or typewriters because the Keybowl uses a totally new data entry concept. However, the Keybowl's character arrangement and design are possible contributors to the variability. The specific key layout and keyboard design might have put some constraints on some of the subjects with certain hand characteristics (anthropometric and biomechanical) in executing some or all movements which ultimately affected their performance. For example, people with very small hands may have problems placing their hands over the bowl and were thereby unable to move the bowl as discretely as others with larger hands. In addition, the experienced typist's mental model was applied to the Keybowl's character layout providing a basis for subject intravariability based on the aforementioned experience factor.

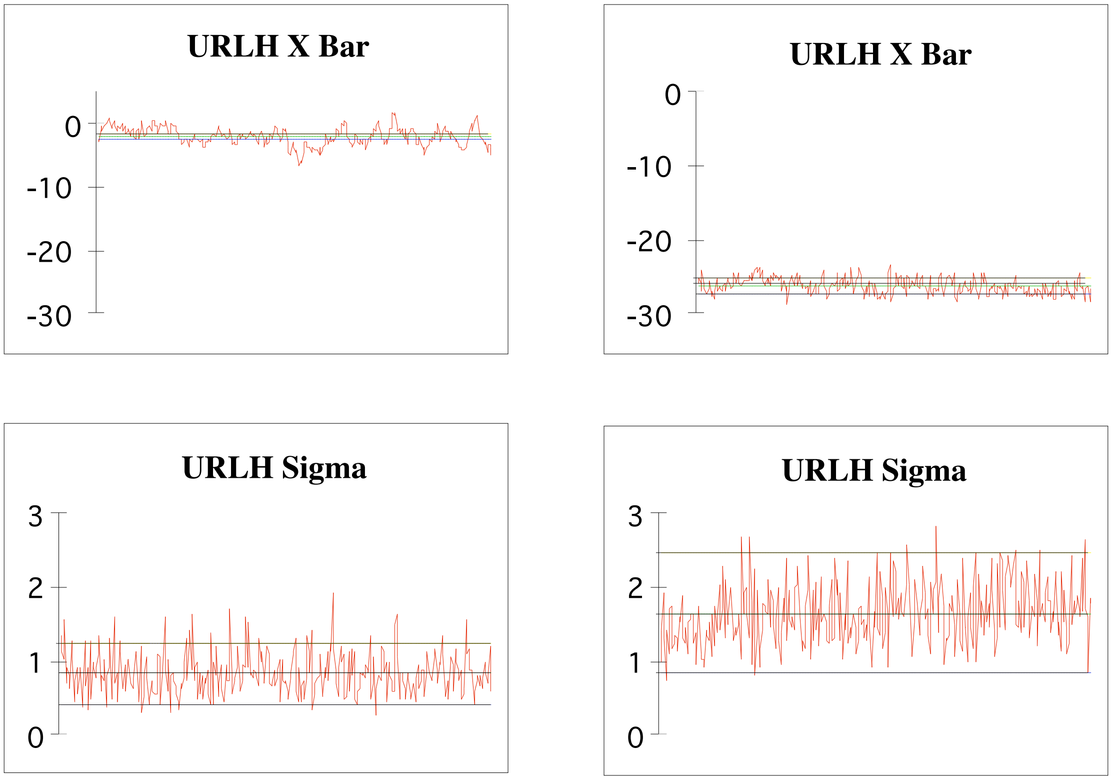
Within and between group homogeneity was extremely important in minimizing confounds in the study. Memory and spatial abilities influenced how quickly one acquired the typing skill. In general, the greater the abilities, the quicker one learns. Each keyboard group was tested for spatial and memory abilities. Typing proficiency is also extremely important. Without an equal baseline performance measure between the two groups, experimental keyboard performances would have been much more difficult to evaluate. Typing tests were administered as a prescreening mechanism for group experience comparison. The groups were not significantly different in terms of spatial, memory, or typing capabilities.

Control Chart Discussion

In the typing process, a certain amount of natural wrist movement variation exists. Natural variation may exist no matter how well the task is designed or taught or how proficient one becomes in typing. Such variation is uncontrollable and results from numerous causes (e.g., hand steadiness, postural stability, etc.). When these variations are stable and relatively small, the process is said to be in statistical control (Banks, 1989). Out of control processes operate in the presence of assignable causes of variation (Banks, 1989). Variability caused by an out of control process can be attributed to the keyboard or the operator (and to some extent the goniometer and characters used in the study). Typing, as performed in this study, was an out of control process (see Figure 39). The typing process may be out of control due mainly to inconsistent finger and wrist motions in per key activation motion. Simply stated, typing the same letter again and again does not necessarily follow a set pattern of finger and/or wrist motion. Movements and finger force requirements vary from single character motions to digram motions (e.g., typing the letters i and e). Even reverse digrams require different motions (e.g., typing the letter e and i)(see Gatewood, 1920, cited in Kroemer, 1993b; Klein & Malzahn, 1991). In addition, wrist repositioning over time contributes to this variability. As finger and wrist muscles start to fatigue, the hands, and thereby the wrist, are constantly re-adjusted into less fatiguing positions. With the newly position wrist, the key activation's once again require different motions.

In reference to excessive finger extensions, some fingers are forced to assume compromising positions to compensate for the shoulder breadth to keyboard width differential. The breadth of shoulders of most users exceeds the width of the keyboard. Because of this differential, some fingers are fully flexed while others are fully extended. Such finger positions reduce the effectiveness of the controlling muscles and also require the muscles to exert constant static contractions to maintain such positions (Rose, 1991). The shoulder breadth to keyboard width differential in combination with the pronation of the hand contributes to perhaps the most researched detriment– ulnar wrist deviation. The wrist is typically deviated toward the ulnar bone found in the forearm hence the name ulnar wrist deviation. A typist constantly adjusts the static tension of hand pronation with the ulnar wrist deviation in an effort to comfortably type. This constant re-adjustment contributes to the uncontrolled variation as discussed above. It is primarily due to these types of biomechanical limitations that the Keybowl was designed using a rounded surface. The bowl shape, because of its symmetry, allows a typist to maintain a relaxed hand posture (position of function) while typing.

Numerous psychological conditions, such as boredom and frustration, play a role in typing inconsistency. Although processes were out of control for each subject in each group, the data were tested with the Kolmogorov - Smirnov Goodness of Fit Test are were determined to be normally distributed. (see Figures 40, 41, 42, and 43).



(a) (b)

Figure 39. Representative X bar and Sigma control charts for typist in each keyboard group. (a. Keybowl (Session 11); b. QWERTY Keyboard (Session 11)).

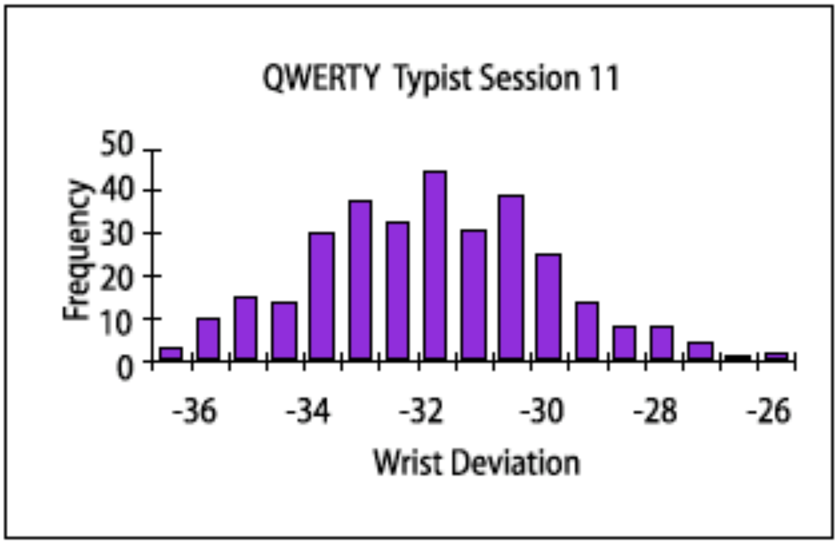


Figure 40. Representative flexion and extension distribution for a typist using the QWERTY keyboard.

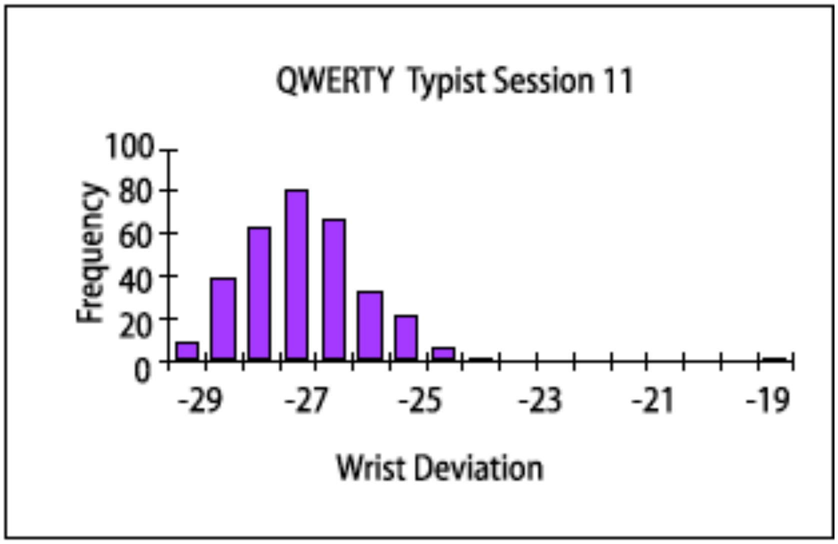


Figure 41. Representative ulnar and radial distribution for a typist using the QWERTY keyboard.

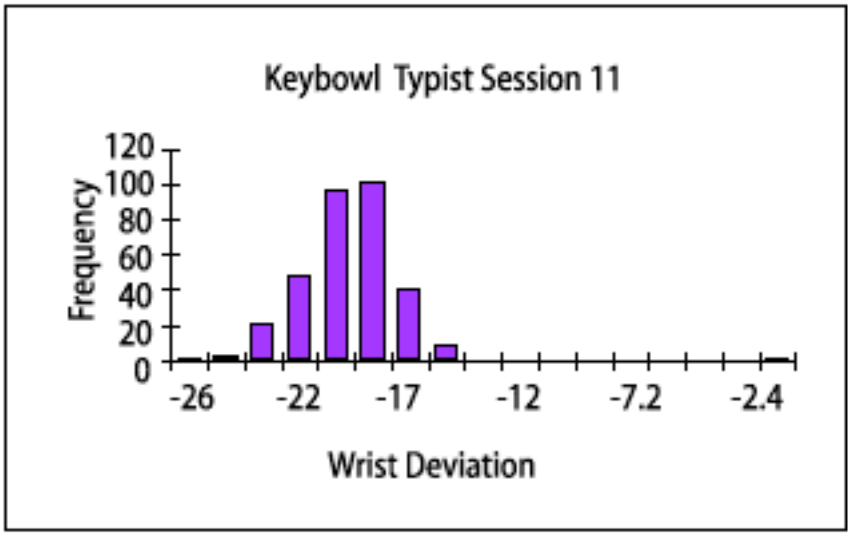


Figure 42. Representative flexion and extension distribution for a typist using the Keybowl.

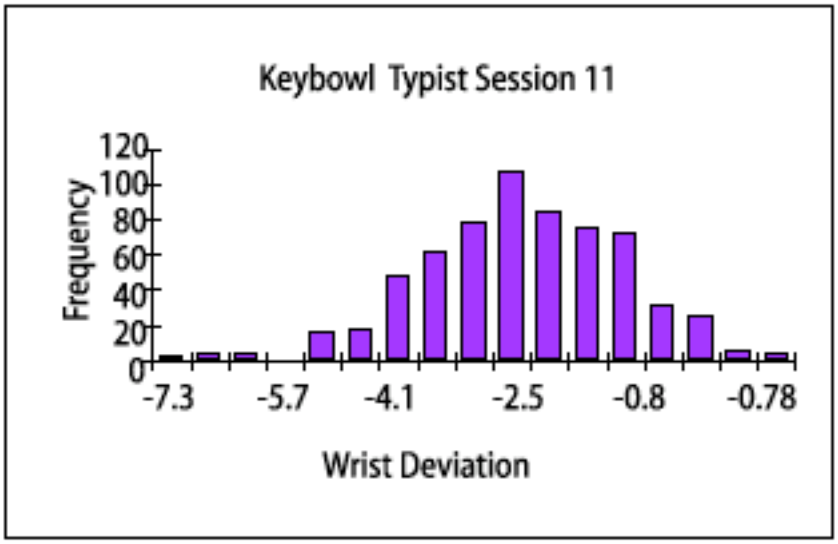


Figure 43. Representative ulnar and radial distribution for a typist using the Keybowl.

Ergonomics

The main objective of analyzing the ergonomic data was to discover whether the two keyboards differ in magnitude and frequency of wrist deviations (see Figures 23-26). The data were analyzed by computing the wrist variance for typing one word. For the approximately 6400 (6 samples/sec x 18.75 minutes/session) data points collected per session, a variance was computed for every 20 data points. The 20 data points represent 3.3 seconds of time (the time to type one word on average). Over one 18 minute 45 second session, 320 variance points were collected. These values were then averaged to determine an average wrist variance for the session.

Ergonomic analysis demonstrated that there were consistent findings between the flexion and extension wrist motions and the ulnar and radial wrist motions. As hypothesized, QWERTY keyboard typists had significantly higher wrist flexion and extension and ulnar and radial motions as compared to Keybowl typists. This was due to the nature of the movements pertaining to control of key activation in each of the keyboards. The Keybowl was designed, although not necessarily optimally, through the prototype used, to eliminate all finger movement and drastically reduce wrist motion. The left hand had significantly higher flexion and extension movements than the right hand. This can be attributed to having better control over ones dominant hand; 28 of the 30 subjects classified themselves as right handed. Studies have shown that the right hand or dominant hand has outperformed the left hand in typing (Gatewood, 1920, cited in Kroemer, 1993b; Hayes & Halpin, 1978). Left hand movements and right hand movements are different. Referring back to Figure 28, the right hand had significantly higher ulnar and radial movements than the left hand. Hence, controlling characters by the right hand requires greater ulnar and radial movements than those controlled by the left hand. The letters H and P require perhaps the greatest ulnar and radial movements (which are both on the right hand). No equivalent character movements are required by the left hand.

It is well documented that females have significantly higher ranges of wrist motions than males. Bell and Hoshizaki (1981) found that women generally exhibited greater ranges of wrist motion than men. In particular, females between the ages of 17 and 30 (95% of the represented sample for this study) had significantly greater flexibility in wrist flexion and extension movements than did males. Additional support to the notion of females having superior range of motion is given by (Cobe, 1928 cited in McDonald, 1992). The results of this study indicated that females have a greater range of motion when typing when compared to males. As previously mentioned, several studies indicate that females are more susceptible to carpal tunnel syndrome than are males. Findings, however, typically focused on physiological, biological, or physical wrist size metrics. Very few studies have quantified wrist motions (magnitude and/or frequency) in determining how such movements influence CTS. Methods have been suggested as to how to approach quantifing such movements (see Armstrong, Chaffin, & Foulke, 1979). Several studies have, however, demonstrated that the repetitive nature of the typing task puts a typist at risk of developing a RSI (Moore, Wells, & Ranney, 1991; Stone, 1983; Wilson & Corlett, 1990). How much repetition is often debated. No studies have been uncovered that analyze typing task wrist motions as a contributor to CTS. According to Drury and Hoffmann (1992) the modeling of keyboard motions have not been well documented. There are several reasons for this lack of information: 1) accurate methods for wrist motion analysis have been lacking, 2) the complexity of wrist movement poses special evaluative problems, 3) the influence of finger movement on wrist movement is not well founded, and 4) the factors that may affect or exacerbate CTS are numerous. The findings of this study indicate that female wrist motions (frequency and magnitude) may play a more important role (as opposed to wrist size, hormonal change, etc.) than initially thought in the development of CTS. As such, this study is one of the first to actually quantify dynamic wrist motion as it relates to typing. With regard to wrist motion, the QWERTY keyboard appears to be gender biased whereas the Keybowl appears to be gender indifferent. This is due primarily to the gender difference detected in the QWERTY group. No such gender difference was found in the Keybowl group. This finding may imply that the QWERTY keyboard is "optimized" for males (i.e., users with larger hands and less hand and wrist mobility).

There were also significant differences in wrist motion between the two stages of testing. The results indicate that the random word stage had significantly higher wrist flexion and extension and ulnar and radial movement than did the random character stage. The QWERTY group had significantly higher flexion and extension and ulnar and radial movements in stage 2 compared to stage 1, whereas the Keybowl group had no significant difference between the two stages of testing. For stage 1, the difference can be attributed to the first session, the session in which the subjects had to acclimate themselves to their respective keyboards. In stage 2, however, only the left hand had a significant difference in movement throughout the stage, the right hand was much more stable. The differences exist due mainly to the range of motion in the respective movements, the amount of hand control, or as a function of actual typing speed. The range of hand motion in ulnar and radial planes are about 43% of the flexion and extension movements. In the Keybowl group, typing speeds ranged from 6.3 GWPM to 15.2 GWPM in stage 1 and 16.25 GWPM to

23.5 GWPM in stage 2 compared to 26.3 GWPM to 35.2 GWPM in stage 1 and 38.25 GWPM to 45.5 GWPM in stage 2 for the QWERTY group. Performances for both groups increased by approximately 10 GWPM from the end of stage 1 to the end of stage 2.

The average wrist motions obtained in this study may be slightly inflated with respect to the actual motion. The Penny and Giles electrogoniometers, although extremely sensitive to wrist motions, are prone to the same errors as any electromechanical device. Errors may occur from sources such as electrical interference from the computers, monitors, etc. A study recently performed to determine reliability of the Penny and Giles electrogoniometers demonstrated that 4.5 degrees of error in flexion/extension plane and 4.6 degrees of error in the ulnar/radial plane were possible (McDonald, 1992). It was determined that electrogoniometer errors were more apt to occur at extreme wrist motions (McDonald, 1992). With the significantly higher wrist motions observed in QWERTY keyboard typists, the electrogoniometers may be prone to higher errors due to these greater motions. Further investigation is needed to determine the precise error for each keyboard group. Similarly, the average flexion/extension and ulnar/radial movements (2.7 degrees and 2.35 degrees respectively) for the Keybowl typists may be attributed, in part, to errors in goniometer readings. Results also indicated that there was a crosstalk error between the two movements (e.g., when moving the hand in the flexion and extension plane only, some variance was recorded in the ulnar and radial plane.) This interaction, however, was greatest only when the primary electrogoniometer (flexion and extension) was near its extreme motion. This is an important consideration but is not as important for the typing task analysis due the non-extreme movements of the wrist in the flexion and extension or ulnar and radial plane. Other potential sources of variability include procedural inconsistencies in attaching the goniometers to the subjects, inherent variability of range of motion at the wrist, and variations in electronic equipment. Hellebrandt (1949) and Horger (1990) discovered that intrarater reliability was higher than interrater reliability. These findings suggest that experienced experimenters are able to obtain more consistent results (cited in McDonald, 1992).

In terms of what was learned for new Keybowl design considerations, it was discovered that an adjustable arm rest may be more beneficial than the fixed one used for providing maximum ergonomic advantage and typing comfort. From the discussion of flexion and extension movements, recall that the average wrist position for the Keybowl typists right hand was approximately -10 degrees (-15 degrees for the left hand) (see Figure 23). An adjustable arm rest could reposition the average wrist deviation to 0 degrees, the optimum angle for minimizing fatigue and optimizing comfort. The same benefit could be realized in the ulnar and radial plane by placing the dome slightly off center (approximately 10 degrees) from the midline of the Keybowl. In this study, ulnar and radial averaged approximately 10 degrees of deviation.

Random Character and Random Word Stages

The first stage, the random character stage, was developed for the subjects to learn the keyboard layou. During this stage, the subjects re-familiarized themselves with either the spatial location of the letters on the QWERTY keyboard or the locations of the 16 letters on the Keybowl. Each subject was introduced to a series of random character sessions for learning to type all 16 lower case letters of the English language. At the end of the eighth random character session, the random character stage was terminated and the testing stage begun. No feedback was given to subjects about their performance progress or levels to avoid possible undesired motivational effects based on performance. The end of the 8th random word session concluded the random word stage and the experiment.

The random word stage was similar to the random character stage in that it is comprised of 8 sessions of randomly generated information. A session in the random word stage, however, was composed of randomly generated words, not randomly generated characters. Each session in the random word stage was developed for subjects to gain proficiency by practicing the different word combinations of learned Keyboard movements or QWERTY key actuation. The word sets were randomly generated for each session and each subject. The main objective of analyzing the random word data was to discover whether the two keyboards differed in character throughput based on a word criteria as opposed to a character criteria.

Performance

The results of this study indicated that the mean performance levels (measured in GWPM) of QWERTY typists were greater than mean typing performances of Keybowl typists. The goal of the performance evaluation was to determine if learning rates of the Keybowl and QWERTY keyboards were similar. The only concrete results found came from analyzing actual typing performances. After 5 hours of using the Keybowl, experienced QWERTY typists are able to type approximately 60% of their QWERTY typing speed when typing with the Keybowl. In fact, the typing performances in Keybowl sessions 15 and 16 were almost identical to sessions 1 and 2 of QWERTY keyboard performances. These preliminary results indicate that the Keybowl typists may be able to quickly achieve performance levels comparable to that of QWERTY keyboard typists, while eliminating finger movements and drastically reducing wrist movements.

Performances of the two groups of subjects using the Keybowl and the QWERTY keyboards were expected to be comparable in many ways. With the limited amount of data and the learning rates computed, the acquisition of Keybowl typing skill does not appear to be any more difficult than, or different from, learning to type on a QWERTY keyboard. Although there was a significant difference between the two groups typing performances, the large difference may primarily be attributed to the typists being proficient QWERTY typists before the study began. All were required to be proficient typists because the study's focus was on retraining and ergonomic issues pertaining to the Keybowl. Both skills have the same basic type of memory and retrieval requirements, however, in touch typing, typists have to memorize and retrieve key locations that are associated with characters. In using the Keybowl to type, typists associate character locations with bowl positions. The Keybowl typists indicated that Keybowl typing was easy to learn because of its QWERTY compatible mental model coded character schema and visible character arrangement. The relative perceptual difficulty between the two skill components (i.e., memorizing and retrieving bowl locations as compared to memorizing and retrieving key locations) requires further study. The use of a16 character set placed semi-heavy memory, retrieval, and motoric loads on both groups of subjects. As subjectively noted by the subjects, the 16 characters locations on the Keybowl were memorized in 1 hour and 15 minutes. If the number of characters is increased, however, the relative impact of factors affecting each typing skill may differ and affect performance.

The improvement rate analysis has left many more unanswered questions than it answered; there are several questions that arise from these results. Why are the improvement rates different for the stages in the Keybowl group and not the QWERTY group? The reason why the rate changed from 75% in the random character sessions to 85% in the random word sessions can be in part explained by the stabilization of understanding the typing task required, having the characters and character locations memorized, a practice learning effect, or the completion of the 'break-in' period. According to Cochran (1969) 'break in time', the time before a standard can be established, can be affected by physical adaptation, coordination and dexterity, methods improvements, and increased speed. Why did the QWERTY random character sessions require so much more time as compared to the random word sessions to reach the 60 GWPM proficiency level even though both have the same improvement rate? The time to reach proficiency is high in the random character session due to the improvement rate and number of words required to reach 60 GWPM. The 28.14 GWPM found in session 8 needs to improve by 31.86 GWPM. In addition, all QWERTY typists were required, to some extent, to re-learn how to type individual characters. They were all proficient typists typing approximately 42 GWPM for the first 8 sessions (2.5 hours). Learning occurred due to acclimation of the experimental procedure, the keyboard, a short 'break in' time, and possibly some actual learning. For sessions 9 through 16 learning occurred because of the transition from random characters to random words– a re-learning process was again required. The GOMS analysis may also provide some insight into why the time was so lengthy. When typing random characters, attention must be focused on one character at a time, they must be mentally processed one character at a time, and must be typed one at a time. The process is slowed down enough compared to contextual (i.e., word and sentence structure where information can be chunked) typing to make single character typing more difficult in terms of mental and motor demands and therefore much more time consuming. With only three data points to determine the level of learning, one needs to be cautious in using such a small number of values. In reference to the Keybowl random character and word sessions, how could it be twice as fast to achieve 60 GWPM typing random characters vs. random words when just the opposite holds for the QWERTY group over the same sessions? There are several reasons as to why the learning rate was so high in sessions 1 through 8. Quick adaptation to using the Keybowl could have resulted. Subjects learned character locations within the first 4 sessions. The level of improvement may be attributed to learning character locations, having a limited number of characters to learn, and not being able to correct errors. Another influencing factor may be acclimating to new movements rather quickly. In terms of physical adaptation, different muscle groups used in Keybowl typing may need to be strengthened. The different movements and postures required in Keybowl typing may also require adaptation. Coordination and dexterity skills are required for mastering the motions required in Keybowl typing. Such skills may have been developed rapidly during the first 8 sessions and may have accounted for much of the rapid increase in learning. Keybowl movements may have also required method improvements over the first 8 sessions. Method improvements are often undetectable, minor improvements to the motions required in typing with the Keybowl. During this stage, wrist, hand, and arm postures may be improved and motions may have been combined. These improvements may add up to significant time savings. Increases in speed often result from the improvement of the aforementioned concepts. The improvement due to speed increase alone is limited to one-third of the total reduction (Cochran, 1969).

Another factor that has a direct affect on the interpretation of such results is the part of the learning curve being analyzed. The subjects were all experienced typists and performances were based on past learning (i.e., a continuation of a past learning). Even for the Keybowl typists, learning was transferred from their QWERTY typing skills. As such, it is extremely difficult to determine where on each learning curve the subjects' performances lie without knowing where the two groups started. One potential solution is to compare QWERTY typing performances determined in other studies and compare and correlate them to QWERTY performances found in this study to determine which part of the learning curve is being analyzed. Once determined, the information <u>may</u> be able to provide insight on how past performances of Keybowl learning compare. This may be inappropriate because of the differences in traditional methods of typing and the method employed. Future research should be directed toward how novice typists acquire the Keybowl typing skill to round out a complete learning curve analysis.

<u>Performance as a function of wrist movement</u>. As previously mentioned, several factors played a role in wrist movements between gender and the two keyboards. The QWERTY keyboard group had significantly higher typing speeds than the Keybowl group. Typing speeds, which were also significantly higher in the female group, may account for some of the wrist motion variance between the two genders. The non-significant difference between the genders in the Keybowl group may be attributed more to the design and slower typing speeds compared to the QWERTY keyboard group. Within each keyboard group, no significant performance differences existed between males and

females. However, even with no significant difference in typing speeds within the QWERTY group, the females had significantly higher wrist movements than males.

NASA-TLX Analysis

As with any new type of learning, initial workload is expected to be high. It was therefore expected that the Keybowl typists would experience higher levels of workload initially. Workload was more of an issue for females than males, however. As a highly kinesthetic activity, typing with the Keybowl may cause a higher perceived workload due to the transition from typing with a relatively high finger motion (QWERTY), and in the case of females, higher wrist motion, to one that requires no finger motion (Keybowl). How quickly the workload measures converge is at the forefront of the analysis. Workload measures converged in the last few sessions of each stage (see Figure 44). Perceived workload was significantly higher in the random character sessions when compared to the random word sessions (see Figure 44). It has been well established that typing random characters requires higher levels of concentration, due to mental processing of a single character at a time compared to chunking words, and slower rates of typing for accurate typing, again due to mental processing and psychomotor skills. Overall workload levels of the experienced QWERTY typists using the QWERTY keyboard may have been high initially due to having to literally slow their typing rate for the random character sessions. It was suspected that Keybowl typists had similar levels of workload but for different reasons: new motor skills had to be developed and typing skills had to be re-learned to some degree. The Keybowl's QWERTY mental model adaptation very quickly quelled this workload; Keybowl typists quickly learned character locations to gain typing proficiency. For females, perceived workload was higher for Keybowl than for QWERTY females. Again, this difference can be primarily attributed to learning to type using the Keybowl. For males, a similar, but much less pronounced, difference was found between using the Keybowl and the QWERTY keyboard. As subjects progressed through the sessions in each of the stages (i.e., became more adept in using their keyboard), the difference between Keybowl workload and QWERTY workload lessened. In fact, the last two sessions of experimentation showed that workload was actually lower for the Keybowl group than it was for the QWERTY group (see Figure 44). The Keybowl's perceived workload, if examined over a longer period of time, may actually be less than the perceived workload of those using the QWERTY keyboard. It should also be noted that external factors, tiredness, school stress, etc. may have influenced perceived typing task workload.

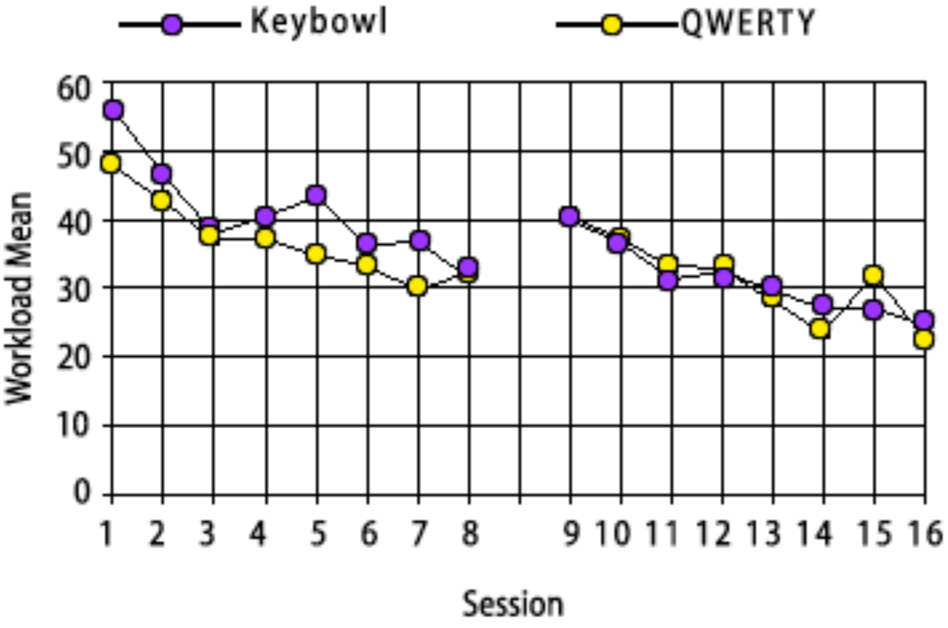


Figure 44. Weighted workload averages over each session of testing.

Questionnaire

Correlations between questionnaires were high (96.2%). With such a high agreement it was determined that the experiences between the two stages were comparable. The subjects' subjective experiences were not expected to be significantly different with the exception of two factors: ease of use of keyboard and fatigue factors. The other factors pertaining to typing performance, meaningfulness, personal satisfaction, and importance were not significantly different. Ease of use differences can be primarily attributed to subjects knowledge and use of the QWERTY keyboard. Differences in having to type with something the subjects knew how to use versus something new is believed to be the essence of the ease of use significant difference.

Fatigue factors in the wrist and hand were significantly lower in the Keybowl as compared to the QWERTY keyboard. It was expected that the Keybowl required significantly less wrist, finger force, and movement to type and may therefore have significantly lower muscle activities at the wrist, forearm, and shoulder. There are a few factors that contribute to this difference: The elimination of finger movement, the elimination, or minimization of wrist movement, and the amount of movement required to activate a character. Recall the whole purpose of the Keybowl design was to eliminate these fatigue factors. It was therefore expected that such a difference existed.

Perceived stress at the shoulder, however, was not significantly different. The stress at the shoulder between the two keyboards was not expected to be any greater for Keybowl when compared to the QWERTY. Typing duration, shoulder musculature, and low frequency of use are factors that influence the stress at the shoulder when typing. Recall that each session was only 18 minutes and 45 seconds in duration. As such, the comparatively large muscles in the shoulder as compared to the wrist and fingers may have not been used for a long enough period of time for a subject to sense the fatigue. In addition, the workstation VDT guidelines adopted and instituted reduced the amount of static fatigue in the shoulder. The workstation was adjusted such that arms were placed in an ergonomically correct position while typing. The amount of arm, and in turn shoulder, movement was also a function of how far a typist had to reach to activate a character. For this study, no far reaching keys on the QWERTY keyboard were used (e.g., delete, esc, the numerics). The distance the little finger moves when typing with a regular QWERTY keyboard is about 2 inches from the ; key (pinky home row position) to the delete (or backspace) key. A significant difference in shoulder fatigue may have been found had these longer reach keys been used. In typing with the Keybowl, the distance is always a fixed distance from the bowl's pivot point; the amount of movement to activate any of the characters was 4 mm.

Error Analysis

A problem that experienced typists may have in using the Keybowl rests is memorizing chord locations. Even though a GOMS analysis, an analysis of the typing task in terms of its most basic components has proven that mental models from the QWERTY layout can, to some degree, be ported to the Keybowl layout, there still exists the linear vs. circular disparity. No literature has been found that describes how to map a linear key layout to a circular key layout. Keying rates are also an issue based on the GOMS analysis. Because the Keybowl uses a chordal method of key activation, activation is fundamentally different from the

QWERTY key activation. The GOMS analysis, with its associated quantitative keying times, gives an experimenter great insight on how keying rates and errors differ.

Key loads were balanced per hand (8 keys) but not per finger (see Figure 45). The index and middle fingers controlled over two-thirds of the keys. With regard to the rows of keys, the amount of work performed using the reduced set of 16 characters is comparable, in terms of finger workload, to the workload of using a full character set (see Figure 46). The characters i, o, and n had the highest number of errors for the QWERTY group (in the random word sessions only). It is interesting to note that all three characters are controlled by the right hand, the hand that was in ergonomically better control in the flexion and extension plane, but not in the ulnar and radial plane. Could there be some correlation between the magnitude of ulnar and radial movements and the number of errors? Characters controlled by the left hand, throughout the study, were more stable in terms of error rates. The findings in the literature indicated that keying errors rates are affected by speed, but little research has been uncovered that analyzed single key error rates. It has been suggested that because of the weakness of the ring and pinky fingers, they fatigue more quickly over time and may therefore be more prone to error than the stronger index and ring fingers (see Kroemer, 1993b). In support of the typing speed vs. error rate notion, a significant difference existed between the random character stage and the random word stage in terms of both speed and number of errors. There are several reasons as to why errors may be higher in the random word stage. Even though the actual number of errors may be higher, the proportion of errors to the number of characters typed is the same for both stages. The Keybowl group did not experience the same type of error increase potentially because 1) typing speeds were slower compared to the QWERTY group, and 2) mental models were not developed well enough to promote kinesthetic typing.

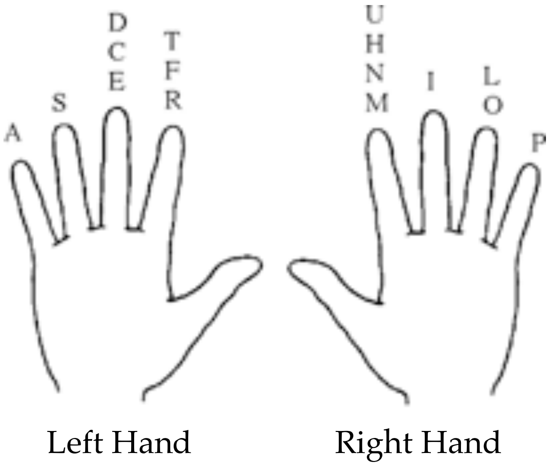


Figure 45. Characters controlled by hand and by finger.

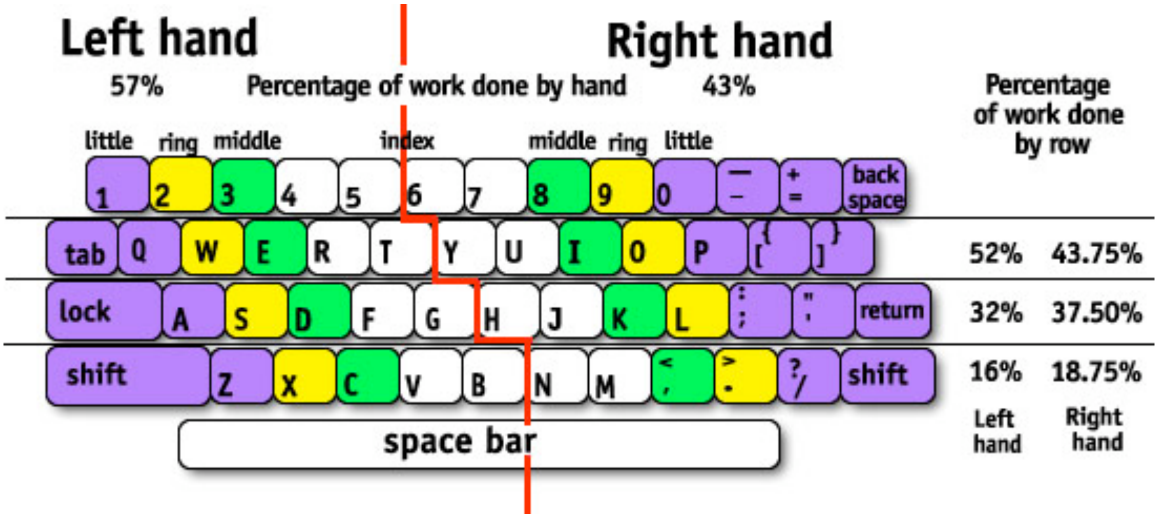


Figure 46. QWERTY keyboard layout with finger and hand control mapping (adapted from Cooper, 1983.) [1] Dvorak, 1943 findings; [2] the proportion of characters used in each row for the 16 characters used in this study.

The differences in error rates between the keyboards can be attributed to several factors: 1) the Keybowl prototype may not have been engineered optimally (no bowl guidance mechanism, no tactile key feedback, etc.), 2) faulty response aiming due to different physical positioning to the Keybowls and/or hands, or 3) biomechanical aspects of character activation (re-coordinating muscles to type with the Keybowl). The prototype was designed to match the characteristics of its QWERTY counterpart. Both required 0.7 N of force with 4 mm of displacement for character actuation. The Keybowl was also designed without a guidance mechanism for accurate dome movement. This was done on purpose to determine if the eight character locations could be activated without such guidance. From the results obtained and the comments received from the subjects, a guidance mechanism would be beneficial. Typing accuracy was fairly consistent throughout the sessions for both keyboards, however. Design or biomechanical constraints are more likely to cause the difference in errors because of the key actuation methods employed. Psychological issues may also play an important role. There may be some innate difficulty in re-learning to type in a circular layout after typing with a linear one. Further investigation is required to determine if psychological differences do in fact play a role in error rates.

Even though the number of errors were different between hands and between stages, the proportion of errors for each character location of the Keybowl was fairly well balanced. The letters c on the left hand bowl, and l on the right hand bowl were the only two characters that were proportionally out of line with the rest of the characters (c 19%, and l 19%)(refer to Figure 35 for character locations). The ramifications of having a balanced proportional error rate are two-fold: 1) balanced positional error rates may indicate that any one key position is neither significantly easier nor more difficult to actuate than any other key and 2) orientation of dome with respect to character locations may have influenced the number of errors for each character. The dome placed in a different orientation, whether it be in the vertical or horizontal plane, may change the proportion of errors. These findings indicate that the eight positions for character locations are not biomechanically or motorically different for per character actuation criteria.

Character error analysis provides significant insight into which character combinations, and therefore chords, have the highest actuation accuracy. The letters c and l, controlled by the left and right hands respectively, had the highest error rates on a per hand basis. The bowl positions in which these two characters are contained should be used for the least used characters (e.g., the letter x) when devising a chord scheme using the two positions. The converse is also true. The letters d and p, controlled by the left and right hands respectively, had the lowest error rates on a per hand basis. These two positions should be coded such that the chord combination of these two positions contain the most frequently used characters (e.g., the letter e).

Areas of Future Research

Although this work is the first contributing to the body of knowledge concerning the Keybowl, it is not comprehensive and much work with regard to its design and chord schema remains to be done. One study, in particular, that would provide a great deal of insight is a comparison between the experimental results found by Raij and Gopher (1987) (a study on perceptual and motor determinants of efficient data entry), to the results found on the Keybowl. Extensive experimental work is needed to develop optimal chord coding and design configuration for the Keybowl. Anthropometric, cognitive, and biomechanical characteristics of potential users of the Keybowl should be used as guidelines to help achieve an optimal design of the device. In general, the scope of any future research should cover: chord coding, design configuration, and different performance analyses. Also, further research is needed to fully explain and define skill requirements, perceptual and motoric, of chord typing.

The Keybowl's design has been shown to eliminate finger movement and drastically reduce wrist motion. For these reasons, it is expected that the Keybowl will have significantly lower muscle activities at the wrist, forearm, and shoulder (see Tichauer, 1966). Electromyographical (EMG) studies have been performed on several muscle groups while typing and were used as part of the Kinesis keyboard evaluation (see Basmajian & DeLuca, 1985; Bendix & Jessen, 1986; and NIOSH, 1990). EMG analyses should be performed while using the Keybowl to determine if muscle activities are reduced as a function of wrist and finger movement reduction. Such analysis would be useful in determining whether or not the larger muscle groups (shoulder and forearm) were more active while typing with the Keybowl when compared to the QWERTY keyboard measures. The optimal situation would be one in which the muscle activities along the whole upper extremity were significantly lower for the Keybowl when compared to any other keyboard.

Novice and experienced typists should be used to gain a better understanding of learning rates and to establish a more accurate and representative comparison. Moreover, the period of time in using each keyboard to determine precisely how performances compare should be extended. Determine if wrist movements increase as typing speed increases for the Keybowl and keyboard. For the keyboard, the relationship has already been established. In addition, use of an appropriate distribution of characters, as opposed to the ones most frequently used, would provide a better understanding of which characters have higher error rates, etc. in actual typing. The vowels, for example, should be used more often because they are typed more often than the rest of the characters. In this study, all characters were represented equally. The letters should follow the same distribution in which they are used in text and everyday usage (e.g., a is the most commonly used letter in the English alphabet, h the 16th, "a" should therefore be used x times greater than h.)

Similar experimental approaches to the one provided in this study should be considered and devised to determine the perceptual and motor difficulties of different chord combinations on the Keybowl. This could be done through a more complete analysis of error rates; perform analyses on errors of insertion, omission, substitution, transposition, and other (see Cooper, 1983). These analyses may provide valuable insight as to what the different types of errors are between the two keyboards and which chord combinations could be used to maximize typing speeds. The specific issues to be addressed are the independence of motor and perceptual measures and their relative contribution to chord typing. The chord quantification measures can be based on work completed by Ratz and Ritchie (1961). They suggested that chords be ranked according to chord typing reaction times by subject in response to a visual stimulus representing the chords. The ranking is indicative of the relative perceptual difficulty between chords. The quickest chords, based on reaction times, should be assigned to the most frequently used letters. 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 include (Fathallah, 1988):

- 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 statistics).

- Frequency of occurrence of letters in the text– As previously mentioned, 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.

- 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.

- 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".

Optimal character layout must also be analyzed with regard to chordal mapping as opposed to an adoption of an existing layout. The QWERTY layout is not necessarily the best layout for any keyboard, especially a chordal keyboard. Chord keyboards are often forced to adopt different character mappings due to reduced key sets and actuation methods. The Keybowl, however, is in a unique situation to adopt either its own layout or one that already exists. It is much better suited in providing a QWERTY equivalent than most other chord keyboards because of its demonstrated congruent character schema. Further research should be performed to determine how different layouts affect performance.

Color coding for rapid identification of characters and bowl movements for Keybowl need to be investigated. With a sixty four character Keybowl, eight colors need to be considered. Character color, as well as size, also needs to be considered. Character recognition is affected by the background color upon which the character rests. Black characters on a gray background may be more difficult to identify than black characters on a white background. Color use and lighting are also important considerations. Depending on where the Keybowl is to be used, different color schema may need to be used to optimize character recognition. In fact, eight pattern rings, as opposed to color rings, may prove more beneficial in such situations. For color blind individuals, shades of gray may prove to be the best arrangement for character identification on the Keybowl. In addition, some combination of color, grays, and/or patterns may provide an appropriate means of character identification for low vision individuals.

It was assumed that letters assigned to chords that are considered easy to perform (e.g., executed by the strongest hand movements: up, down) would yield faster reaction times and higher accuracy. Analysis of the speed and accuracy of execution of each character individually, and with respect to other characters, may be needed to allow for a thorough explanation of the existing relationships. It may also help quantify how well the actual prototype of the Keybowl worked. This analysis would aid in explaining the perceptual and motoric difficulties of individual chords and would be part of the process of reaching an optimal coding schema for the Keybowl. Some possible analyses that can be conducted include a detailed error analysis of chord execution, performance comparison between letters when assigned to the same chords, and other chord remapping. These analyses would help determine whether or not letters have inherent differences in their perceptual difficulty.

How do perceived workloads compare between the two keyboard groups when both groups are novice typists? Would the workload levels be the same at each stage of learning to type using the Keybowl and QWERTY keyboards? The acquisition of typing skill can have very high levels of workload associated with it depending on how it is taught. There are a few potential reasons as to why such levels of workload exist: 1) motor skill development can be a tedious process and 2) mental workload is high initially (an individual's memory and spatial abilities play an important role in the mental processing of character locations). It would be interesting to determine if the same types and levels of workload were encountered for typists using the Keybowl, a device that requires much different motor skill development than its QWERTY counterpart.

Anthropometric studies would provide insight into a few of the flexibility characteristics of the Keybowl. Different bowl sizes may play a role in a performance/ergonomic advantage. An experiment could be run that uses "optimal" size domes (domes that are designed to "fit" the subjects hands) vs. a single size dome to determine if dome size plays a significant role in typing performance and/or ergonomics (see Kroemer, 1989; NASA, 1978). In addition, various bowl force and bowl displacements could be modeled and tested to determine optimal character throughput based on force and displacement characteristics (see Loricchio, 1992).

Lastly, and most importantly, the Keybowl should be evaluated for its potential in offering those individuals with varying finger, hand, and/or arm abilities a means of communication. After all, the belief that it could one day become a useful device in allowing the handicapped some form of independence is why it is in existence today (see Bousisset & Rossi, 1991; Casali & Williges, 1990; Marley, Malzahn, & Fernandez, 1987).

References

Abernethy, C. N. and Hodes, D. G. (1987). Ergonomically determined pointing device (mouse) design. Behaviour and Information Technology, 311-314.

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

Amadio, P. C. (1992). Historical review: The Mayo Clinic and Carpal Tunnel Syndrome. Mayo Clinic Proceedings, 67, 42-48.

Are CTDs the next lawsuit bonanza? (1992, March). CTD News, pp. 1-3.

Armstrong, T. J. and Chaffin, D. B. (1979). Some biomechanical aspects of the carpal tunnel. Journal of Biomechanics, 12, 567-570.

Armstrong, T. J. and Chaffin, D. B. (1979). Carpal tunnel syndrome and selected personal attributes. Journal of Occupational Medicine, 21(7), 481-486.

Armstrong, T. J., Chaffin, D. B., and Foulke, J. A. (1979). A methodology for documenting hand positions and forces during manual work. Journal of Biomechanics, 12, 131-133.

Arndt, R. (1987). Work pace, stress, and cumulative trauma disorders. Journal of Hand Surgery, 12A (5:2), 866-869.

Banaji, F. M. M. (1920). Keyboard for typewriters. Specification of letters patent, U. S. Patent No. 1,336,122.

Banks, J. (1989). Principles of quality control. John Wiley & Sons, Inc., New York.

Barranco, S. and Strelka, E. (1976). Carpal tunnel syndrome. Virginia Medical Monthly, pp. 103-122.

Bartholomew, D. (1992 November 9). RSI: Is it your problem? Information Week, pp. 32-44.

Basmajian, J. V., and DeLuca, C. J. (1985). Muscles alive: Their functions revealed by electromyography, 5th Ed. Williams and Wilkins, Baltimore.

Bell, R. D. and Hoshizaki, T. B. (1981). Relationship of age and sex with range of motion of seventeen joint actions in humans. Canadian Journal of Applied Sport Sciences, 6(4), 202-206.

Bendix, T. and Jessen, F. (1986). Wrist support during typing- a controlled, electromyographic study. Applied Ergonomics, 17(3), 162-168.

Bergos, R. (1960). An analysis and comparison of typescript error made on electric typewriters with those made on non-electric typewriters. The National Business Education Quarterly, 29(4), 9-10.

Biegel, R. A. (1934). An improved typewriter keyboard. The Human Factor, 8, 280-285.

Birbeck, M., and Beer, T. C. (1975). Occupation in relation to the carpal tunnel syndrome. Rheumenology Rehabilitation, 14, 218.

Blair, S. J., and Bear-Lehman, J. (1987). Editorial comment: Prevention of upper extremity occupational disorders. The Journal of Hand Surgery, 12A, 821-825.

Blackstone, E. G., and Smith, S. L. (1937). Improvement of Instruction in Typewriting. Prentice-Hall, Inc., New York.

Book, W. F. (1908). The psychology of skill: Three studies. University of Montana Publications.

Bousisset, S. and Rossi, J. P. (1991). Ergonomics, situational handicap, and new technologies. Ergonomics, 34(6), 791-797.

Brogmus, G. E., and Marko, F. (1992). The proportion of cumulative trauma disorders of the upper extremities in U.S. industry. Proceedings of the

Human Factors Society 36th Annual Meeting, Santa Monica, CA: Human Factors Society, 997-1001.

Brunner, H., and Richardson, R. M. (1984). Effects of keyboard design and typing skill on user keyboard preferences and throughput performance. Proceedings of the Human Factors Society 28th Annual Meeting, Santa Monica, CA: Human Factors Society, 267-271.

Buchholz, B., Armstrong, T. J., and Goldstein, S. A. (1992). Anthropometric data for describing the kinematics of the human hand. Ergonomics, 35(3), 261-273.

Butterbaugh, L. C. (1982). Keying logics for alphanumeric keyboards and human performance. Proceedings of the Human Factors Society 26th Annual Meeting, Santa Monica, CA: Human Factors Society, 634-638.

Callaghan, T. F. (1989). The utility of a technique for testing the differences in ease of chords on the ternary chord keyboard. Unpublished masters thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Callaghan, T. F. (1991). Differences in execution times of chords on the ternary chord keyboard. Proceedings of the Human Factors Society 35th Annual Meeting, Santa Monica, CA: Human Factors Society, 857-861.

Cambridge, C. A. (1990). Range of motion measurements of the hand. In J. M. Hunter, L. H. Schneider, E. J. Mackin, & A. D. Callahan (Eds.), Rehabilitation of the Hand: Surgery and Therapy, (3rd ed., pp. 82-92). St. Louis: C. V. Mosby.

Canon, L. J., Bernacki, E. J., and Walter, S. D. (1981). Personal and occupational factors associated with carpal tunnel syndrome. Journal of Occupational Medicine, 23, 255-258.

Card, S. K., and Moran, T. P. (1980). The keystroke-level model for user performance time with interactive systems. Communications of the ACM, 23(7) 396-410.

Card, S., Moran, T. and Newell, A. (1983). The psychology of human-computer interaction. Hillsdale, New Jersey: Erlbaum.

Card, S. K., English, W. K., and Burr, B. J. (1978). Evaluation of mouse, rate-controlled isometric joystick, step keys, and text keys for text selection on a CRT. Ergonomics, 21(8), 601-613.

Carlson, R. (1963). Predicting clerical error in an EDP environment. Datamation, 9, 34-36.

Casali, S. P., and Williges, R. C. (1990). Data bases of accommodative aids for computer users with disabilities. Human Factors, 32(4), 407-422.

Chaffin, D. B. (1975). Ergonomics guide for the assessment of human static strength. American Industrial Hygiene Association Journal, 36, 505-511.

Chapnik, E., and Gross, C. M. (1987). Evaluation, office improvements can reduce VDT operator problems. Occupational Health & Safety, July, 34-37.

Cochran, E. B., (1969). Learning: New dimensions in labor standards. Industrial Engineering, pp. 38-47.

Cocking, R. W. (1970). In place of QWERTY. Daily Telegraph Supplement, No. 301.

Cohen, J. (1977). Statistical power analysis for behavioral sciences (Rev. ed). New York: Academic Press.

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

Conrad, R. (1965). Short-term memory factor in the design of data-entry keyboards. Journal of Applied Psychology, 50, 353-356.

Conrad, R., and Hill, A. J. (1968). The preferred layout for numerical data-entry keyboards. Ergonomics, 11, 165-173.

Cooper, W. E. (Ed.) (1983). Cognitive aspects of skilled typewriting. Springer-Verlag, New York.

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

Creamer, L. R., and Trumbo, D. A. (1960). Multifinger tapping performance as a function of the direction of tapping movements. Journal of Applied Psychology, 44, 376-380.

Current, R. N. (1954). The typewriter and the men who made it. University of Illinois Press.

DeKrom, M. C., Knipschild, P. G., Kester, A. D. M., and Spaans, F. (1991). Testing for carpal tunnel syndrome. The Lancet, 338(16), 1280.

Diehl, M. J. and Seibel, R. (1962). The relative importance of visual and auditory feedback in speed typewriting. Journal of Applied Psychology, 46, 365-369.

Dolenc (1989). Ergonomic keyboard input device, U. S. Patent Number 4,849,732.

Dreyfuss, H. (1959). Anthropometric data. Whitney Publications: New York, NY.

Drury, C. G., and Hoffmann, E. R. (1992). A model for movement time of data-entry keyboards. Ergonomics, 35(2), 129-147.

Dunn, A. G. (1971). Engineering of the typing keyboard from the human factors viewpoint. Computers and Automation. pp. 32-33.

Duncan, J., and Ferguson, D. (1974). Keyboard operating posture and symptoms in operating. Ergonomics, 17(5), 651-662.

Dunnan, J. B., and Waylonis, G. W. (1991, March). Wrist flexion as an adjunct to the diagnosis of carpal tunnel syndrome. Archives of Physical Medicine and Rehabilitation, 72, pp. 211-213.

Durkan, J. A. (1991, April). A new diagnostic test for carpal tunnel syndrome. The Journal of Bone and Joint Surgery, 73(4), 535-538.

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

Dvorak, A. (1943). There is a better typewriter keyboard. National Business Education Quarterly, 11, 58-66.

Eastman Kodak Company, Ergonomics Group. (1986). Ergonomic design for people at work (vols. 1 and 2). New York: Van Nostrand Reinhold.

Einbinder (1982). Ergonomic keyboard input device, U. S. Patent Number 4,332,493.

Emmons, W. H., and Hirsch, R. S. (1982). Thirty millimeter keyboards: How good are they? Proceedings of the Human Factors Society 26th Annual Meeting, Santa Monica, CA: Human Factors Society, 425-429.

Fathallah, F. (1988). An experimental comparison of a ternary chord keyboard with the QWERTY keyboard. Unpublished masters thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Ferguson, D., and Duncan, J. (1974). Keyboard design and operating posture. Ergonomics, 17, 731-744.

Ferguson, D. R. (1987). "RSI": putting the epidemic to rest. The Medical Journal of Australia, 147, 213-214.

Flanagan, C., Fivars, G., and Tuska, S. A. (1959). Predicting success in typing and keyboard operation. Personnel & Guidance Journal, 37, 353-357.

Fox, J. G., and Stansfield, R. G. (1964). Digram keying times for typists. Ergonomics, 7, 317-320.

Friedman, G. L. (1992). Portable computer keyboard for use with one hand. National Aeronautics and Space Administration Tech Brief, 16(11), 1a-10a.

Gambaro, T. L. (1993). Ergonomic keyboard input device, U. S. Patent Number 5,178,477.

Galitz, W. (1965). CRT keyboard human factors evaluation. UNIVAC, Systems Application Engineering.

Gallie, E. J. (1960). The stenowriter system. IBM research report RC-308.

Garrett, J. W. (1971). The adult human hand: Some anthropometric and biomechanical considerations. Human Factors, 13, 117-131.

Gatewood, E. L. (1920). Individual finger reactions. Psychological Monograph, 28 (Whole No. 4) (in Kroemer, HCI)

Gilbert, W. A. (1930). The orthographic keyboards. Spokane, Washington: Shaw and Borden Co.

Gillan, D. J., Holden, K., Adam, S., Rudisill, M., & Magee, L. (1990). How does Fitts' law fit pointing and dragging? Proceedings of ACM CHI'90 Conference on Human Factors in Computing Systems, Association of Computing Machinery, 227-234.

Glencross, D., Bluhm, N., and Earl, J. (1989). A field study report of intensive computer keyboard training with schoolchildren. Applied Ergonomics, 20(2), 131-135.

Goodman, R. C. (1992, April). An aggressive return-to-work program in surgical treatment of carpal tunnel syndrome: A comparison of costs. Plastic and Reconstructive Surgery, pp. 715-717.

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

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

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

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

Gopher, D. (1986). Experiments with a two-hand chord keyboard: The structure and acquisition process of a complex transcription skill. Israel Institute of Technology, Technical Report Number HEIS-86-5.

Grandjean, E. (1987). Ergonomics in Computerized Offices. New York: Taylor & Francis. (pp. 150-154).

Grandjean, E. (1988). Design of VDT workstations. Handbook of Industrial Engineering, Salvendy, G. (Ed.). New York: Wiley.

Green, R. A., Briggs, C. A., and Wrigley, T. V. (1991). Factors related to working posture and its assessment among keyboard operators. Applied Ergonomics, 22(1), 29-35.

Griffith, R. T. (1949). The minimotion typewriter keyboard. Journal of the Franklin Institute, 248, 399-436.

Guinness Book of World Records. (1992). New York, N.Y.: Bantam Books.

Haaland, J., Wingert, J., and Olson, B. A. (1963). Force required to activate switches, maximum finger pushing force, and coefficient of friction of mercury gloves. Honeywell Memorandum.

Haaland, J. (1962). Anatomic and physiological consideration of the use of the thumb for manual control in space flight. Honeywell Memorandum.

Hagberg, M., and Wegman, D. H. (1987). Prevalence rates and odds ratio of shoulder-neck diseases in different occupational groups. British Journal of Industrial Medicine, 44, 602-610.

Hall, W. and Morrow, L. (1988). "Repetition strain injury": An Australian epidemic of upper limb pain. Social Science and Medicine, 27, 645-649.

Hallbeck, M. S. (1990). Biomechanical analysis of carpal flexion and extension. Unpublished doctoral dissertation, IEOR Department, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Hancock, W. M., and Bayha, F. H. (1982). The learning curve. Handbook of Industrial Engineering, Salvendy, G. (Ed.). New York: Wiley.

Harkins, W. H. (1965). Switch system for consoles. Industrial Design, 1-7.

Hart, S. G., and Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theorectical research. In P. A. Hancock & N. Meshkati (Eds.), Human Mental Workload (pp. 139-183). North-Holland: Elsevier.

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

Herrin, G. D. (1992). Control of overexertion injuries. Paper Presented at Human Factors Engineering, University of Michigan, Ann Arbor, MI.

Hill, G. W., Gunn, W. A., Martin, S. L., and Schwartz, D. R. (1991). Perceived difficulty and user control in mouse usage. Proceedings of the Human Factors Society 35th Annual Meeting, Santa Monica, CA: Human Factors Society, 295-299.

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

Hobday, S. W. (1988). A keyboard to increase productivity and reduce postural stress. In F. Aghazadeh (Ed.), Trends in Ergonomics/Human Factors V. New York: North-Holland. 321-330.

Hodes, D., and Akagi, K. (1986). Study, development, and design of a mouse. Proceedings of the Human Factors Society 30th Annual Meeting, Santa Monica, CA: Human Factors Society, 900-904.

Hopkins, A. (1990). The social recognition of repetition strain injuries: An Australian/American comparison. Social Science Medicine, 30, 365-372.

Howell, C. and Kreidler, L. (1963). Information processing under contradictory instructional sets. Journal of Experimental Psychology, 65, 30-46.

Hunting, W., Grandjean, E., and Maeda, K. (1980). Constrained postures in accounting machine operators. Applied Ergonomics, 11(3), 145-149.

Jahns, D. W., Litewka, J., Lunde, S. A., Farrand, W. P., and Hargreaves, W. R. (1991). Learning curve and performance analysis for the Kinesis ergonomic keyboard: A pilot study. Poster Presentation at the Human

Factors Society 35th Annual Meeting, Santa Monica, CA: Human Factors Society.

Jellinek, H. D., and Card, S. K. (1990). Powermice and user performance. Proceedinngs of ACM CHI'90 Conference on Human Factors in Computing Systems, Association of Computing Machinery, 213-220.

Jetzer, T. C. (1991, February). Use of vibration testing in the early evaluation of workers with carpal tunnel syndrome. Journal of Occupational Medicine, 33(2), pp. 117-120.

Kaiser, J. S. and Koeneman, J. B. (1994). Functional evaluation of the Datahand key entry system: User experience evaluated by questionnaire. Datahand research report.

Kapandji, I. A. (1982). The physiology of the joints (2nd ed., Volume one). New York: Churchill Livingstone.

Kieras, D. E. (1988). Towards a practical GOMS model methodology for user interface design. Handbook of Human-Computer Interaction. Elsevier Science Publishers B. V. (North-Holland).

Kiesler, S., and Finholt. (1988). The mystery of RSI. American Psychologist, 43, 1004-1015.

Kinkead, R. D. and Gonzalez, B. K. (1969). Human factors design recommendations for touch-operated keyboards-final report (Document 12091-FR). Minneapolis: Honeywell, Inc.

Kinkead, R. (1975). Typing speed, keying rates, and optimal keyboard layouts. Proceedings of the 19th Annual Meeting of the Human Factors Society. Santa Monica, CA: Human Factors Society, 159-161.

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

Klemmer, E. T., and Lockhead, G. R. (1962). Further data on card punch operator performance. Yorktown Heights, N. Y.: IBM Research Center.

Klein, M., and Malzahn, D. (1991). Effects of physical ability on working memory requirements, keystroke rate, and subjective workload of computer input devices. Proceedings of the Human Factors Society 35th Annual Meeting, Santa Monica, CA: Human Factors Society, 261-265.

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

Kroemer, K. H. E. (1989). Cumulative trauma disorders: Their recognition and ergonomics measure to avoid them. Applied Ergonomics, 20(4), 274-280.

Kroemer, K. H. E. (1989). Engineering anthropometry. Ergonomics, 32(7), 767-784.

Kroemer, K. H. E. (1992a). Use and research issues of a new computer keyboard. Proceedings of the Human Factors Society 36th Annual Meeting, Santa Monica, CA: Human Factors Society, 272-275.

Kroemer, K. H. E. (1992b). Avoiding cumulative trauma disorders in shops and offices. American Industrial Hygiene Association, 53(9), 596-604.

Kroemer, K. H. E. (1993). Fitting the workplace to the human and not vice versa. Industrial Engineering, March, pp. 56-61.

Kroemer, K. H. E. (1993b). Operation of ternary chorded keys. International Journal of Human-Computer Interaction, 5(3), July-September, pp. 267-288.

Kvalseth, T. O. (1983). Ergonomics of workstation design. Boston: Butterworth.

Lee, K. H. (1991). Biomechanical models of the finger in the sagittal plane. Unpublished doctoral dissertation, ISE Department, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Levine, J. and Black, E. (1993). Terminal illness: The health hazards of computer work. OS2 Professional, March/April 1993, Volume 1, Number 2.

Light, L. W. and Anderson, P. (1993). Designing better keyboards via simulated annealing. AI Expert, pp. 21-27.

Lockhead, G. R. and Klemmer, E. T. (1962). An evaluation of an 8 key word-writing typewriter. IBM Report Number RC-180. Yorktown Heights, N. Y.: IBM Research Center.

Loricchio, D. F. (1992). Key force and typing performance. Proceedings of the Human Factors Society 36th Annual Meeting, Santa Monica, CA: Human Factors Society, 281-282.

Lu, H. and Aghazadeh, F. (1992). Infogrip chordic keyboard evaluation. Proceedings of the Human Factors Society 36th Annual Meeting, Santa Monica, CA: Human Factors Society, 268-271.

Lutz, G., and Hansford, T. (1987). Cumulative trauma disorder controls: The ergonoimics problem at Ethicon, Inc. Journal of Hand Surgery, 12A, (5:2), 863-866.

MacKenzie, I. S., and Buxton, W. (1992). Extending Fitts' law to two-dimensional tasks. Proceedings of ACM CHI'92 Conference on Human Factors in Computing Systems, Association of Computing Machinery, 219-226.

Marks, L. S. (1985). Touch typing made simple. Doubleday, NY.

Marley, R. J., Malzahn, D. E., and Fernandez, J. E. (1987). Potential factors in movement time: Implications for functional evaluation of individuals with disabilities. In S. S. Asfour (Ed.), Trends in Ergonomics/Human Factors IV (pp. 1103-1110). Elsevier Science Publishers B. V.

McDonald, J. C. (1992). Reliability of the Penny & Giles angular measurement system in motion analysis of the wrist complex. Unpublished masters thesis, Queens University, Kingston, Ontario.

McCauley, R. and Parkinson, R. (February, 1971). The new popularity of the Dvorak simplified keyboard. Computers and Automation, p. 31-32.

McMulkin, M. (1992). Description and prediction of long-term learning of a keyboarding task. Proceedings of the 36th Annual Meeting of the Human Factors Society. Santa Monica, CA: Human Factors Society, 276-280.

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

Miller, P. J. (1985). Assessment of joint motion. In J. Rothstein (Ed.), Measurement in Physical Therapy (pp. 102-136). New York: Churchill-Livingstone.

Miller, I., and Suther, T. W. (1981). Preferred height and angle settings of CRT and keyboard for a display station input task. Proceedings of the Human Factors Society 25th Annual Meeting, Santa Monica, CA: Human Factors Society, 492-496.

Milner, A. P. (1988). A review of human performance and preferences with different input devices to computer systems. Proceedings of the HCI'88 Conference on People and Computers IV, British Informatics Society Ltd, 341-362.

Monty, R. W., Snyder, H. L., and Birdwell, G. G., (1983). Keyboard design: an investigation of user preference. Proceedings of the Human Factors Society 27th Annual Meeting, Santa Monica, CA: Human Factors Society, 201-205.

Moore, M. L. (1984). Clinical assessment of joint motion. In J. V. Basmajian (Ed.), Therapeutic Exercise, (4th ed., 192-224). Baltimore: Williams and Wilkins.

Moore, A., Wells, R., and Ranney, D. (1991). Quantifying exposure in occupational manual tasks with cumulative trauma disorder potential. Ergonomics, 34(12), 1433-1453.

Moore, S. J. (1992, October-December). Carpal tunnel syndrome. Occupational Medicine, 7(4), pp. 741-763.

Morita, M. (1989). Development of new keyboard optimized from standpoint of ergonomics. In M. J. Smith and G. Salvendy (Eds.), Work with computers: Organizational, management, stress, and health aspects, New York: Elsevier, 595-603.

Murphy, L. R., and Hurrell, J. J. (1979). Machine pacing and occupational stress. In R. M. Schwartz (Ed.). New developments in occupational stress (pp. 10-20). Cincinnati: UCLA Conference Proceedings, DHEW (NIOSH).

NASA/Webb (eds.) (1978). Anthropometric sourcebook (3 volumes, NASA Reference Publication 1024, LBJ Space Center, NASA (NTIS, Springfield, VA 22161, Order No. 79 11 734), Houston, TX.

NASA (1986). Task load index. Human Performance Research Group, NASA Ames, CA.

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

Nicol, A. C. (1988). A triaxial flexible electrogoniometer. Biomechanics XI. Amsterdam: Free University.

NIOSH (1990). Surface electromyography procedures manual for use in the industrial setting. National Institute for Occupational Safety and Health, Morgantown, W. Va.

Norman, D. A. and Fisher, D. (1982). Why alphabetic keyboards are not easy to use: Keyboard layout doesn't much matter. Human Factors, 24(5), 509-519.

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

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

Onishi, N., Sakai, K., and Kogi, K. (1982). Arm and shoulder muscle load in various keyboard operating jobs of women. Journal of Human Ergology, 11, 89-97.

Owen, S. (1978). QWERTY is obsolete. Interface Age, 3(1), 56-59.

Penny and Giles (1990). M series twin axis goniometer: Operating instructions manual. Blackwood, Gwent, UK.

Pollard, D., and Cooper, M. B. (1979). The effects of feedback on keying performance. Applied Ergonomics, 10, 194-200.

Pollatschek, M. A. and Gilad, I. (1984). Keyboards: does use effect its design and layout? Byte.

Pollock, W. T., and Gildner, G. G. (1963). Study of computer manual input devices. USAF: Decision Sciences Laboratory, Bedford, Massachusetts, AD 419254.

Price, L. A., and Cordova, C. A. (1983). Use of mouse buttons. Proceedings of the CHI '83 Conference on Human Factors in Computing Systems, New York: ACM, 262-266.

Putz-Anderson, V. (1988). Cumulative trauma disorders: A manual for musculoskeletal diseases of the upper limbs. London: Taylor & Francis.

Raij, D. and Gopher, D. (1987). Perceptual and motor determinants of efficient data entry. Proceedings of the Human Factors Society 31st Annual Meeting. Santa Monica, CA: Human Factors Society, 820-824.

Raikova, R. (1992). A general approach for modeling and mathematical investigation of the human upper limb. Journal of Biomechanics, 25(8), pp. 857-867.

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

Rempel, D., Gerson, J., Armstrong, T., Foulke, J., and Martin, B. (1991). Fingertip forces while using three different keyboards. Proceedings of the Human Factors Society 35th Annual Meeting, Santa Monica, CA: Human Factors Society, 253-255.

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

Riemer, E. (1929). A revised keyboard for the typewriter. Unpublished Master's Thesis, N. Y. University.

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

Rose, M. J. (1991). Keyboard operating posture and actuation force: Implications for muscle over-use. Applied Ergonomics, 22(3), 198-203.

Rosinski, R. R., Chiesi, H., and Debons, A. (1980). Effects of amount of visual feedback on typing performance. Proceedings of the Human Factors Society 24th Annual Meeting, Santa Monica, CA: Human Factors Society, 195-199.

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

Rutledge, J. D. and Selker, T. (1990). Force-to-motion functions for pointing. Proceedings of IFIP INTERACT'90: Human-Computer Interaction, 701-706.

Sauter, S. L., Chapman, L. J., Knutson, S. J., and Anderson, H. A. (1987). Case example of wrist trauma in keyboard use. Applied Ergonomics, 18(3), 183-186.

Sauter, S. L., Schleifer, L. M., and Knutson, S. J. (1991). Work posture, workstation design, and musculoskeletal discomfort in a VDT data entry task. Human Factors, 33, 151-167.

Scales, E. M. and Chapanis, A. (1954). The effect on performance of tilting the toll-operator's keyset. Journal of Applied Psychology, 38, 452-456.

Scott, A. D., and Trombly, C. A. (1989). Evaluation. In C. A. Trombly (Ed.), Occupational therapy for physical dysfunction (3rd ed., pp. 184-286). Baltimore: Williams and Wilkins.

Seibel, R. (1972). Data entry devices and procedures. In Vancott, H., and Kinkade, R. (Eds.), Human Engineering Guide to Equipment Design. Washington, DC: American Institute for Research. pp. 311-345.

Shaffer, L. H. and Hardwick, J. (1969). Errors and error detection in typing. Quarterly Journal of Experimental Psychology, 21, 381-383.

Shiratori, Y. and Obashi, F. (1986). Optimum keyboard layout design and evaluation of its operation. Contemporary Ergonomics, Taylor and Francis, London, UK.

Silverstein, B. A., Fine, L. J., and Armstrong, T. J. (1986). Carpal tunnel syndrome: Causes and a preventative strategy. Seminars in Occupational Medicine, 3, 213-221.

Skandalakis, J. E., Colborn, G. L., Skandalakis, P. N., McCollam, S. M., and Skandalakis, L. J. (1992a, January). The carpal tunnel syndrome: Part I. The American Surgeon, pp. 72-76.

Skandalakis, J. E., Colborn, G. L., Skandalakis, P. N., McCollam, S. M., and Skandalakis, L. J. (1992b, February). The carpal tunnel syndrome: Part II. The American Surgeon, pp. 77-81.

Skandalakis, J. E., Colborn, G. L., Skandalakis, P. N., McCollam, S. M., and Skandalakis, L. J. (1992c, March). The carpal tunnel syndrome: Part III. The American Surgeon, pp. 158-166.

Smith, W. and Cronin, D. (1992). Ergonomic test of the Kinesis keyboard. Global Ergonomic Technologies, Inc. Independent Study.

Stone, W. E. (1983). Repetitive strain injuries. The Medical Journal of Australia, 2, 616-618.

Strong, E. P. (1956). A comparative experiment in simplified keyboard re-training and standard keyboard supplementary training. Washington, DC: General Services Administration.

Sulit, B. (1992). Recurrent problems. Human Resource Executive, pp. 40-42.

Suther, T. W., and McTyre, J. H. (1982). Effect on operator performance at thin profile keyboard slopes of 5°, 10°, 15° and 25°. Proceedings of the

Human Factors Society 26th Annual Meeting, Santa Monica, CA: Human Factors Society, 430-434.

Swanson, R. and Sauter, J.(1993). The relationship of working posture to performance in a data entry task. In M. J. Smith and G. Salvendy (Eds.), Advances in Human Factors/Ergonomics, 19B Human-Computer Interaction, Elsevier. 791-796.

Szabo, R. M. (1992, January). Carpal tunnel syndrome. Orthopedic Clinics of North America, pp. 103-108.

Thomas, M. P. (1972). Human coding performance: A review. LUTERG 66. Loughborough. University of Technology, Internal report.

Tichauer, E. R. (1966). Some aspects of stress on forearm and hand in industry. Journal of Occupational Medicine, 8(2), 63-71.

Thompson, D. A., Thomas, J., Cone, J., Daponte, A., and Markison, R. (1990). Analysis of the TONY! variable geometry VDT keyboard. Proceedings of the Human Factors Society 34th Annual Meeting, Santa Monica, CA: Human Factors Society, 365-369.

Trankle, U., and Deutschmann, D. (1991). Factors influencing speed and precision of cursor positioning using a mouse. Ergonomics, 34(2), 161-174.

U.S. Department of Labor , Bureau of Labor Statistics. (1991). Occupational injuries and Illnesses in the United States by Industry, 1989. Bulletin 2379.

U.S. Department of Health and Human Services (1989). Carpal tunnel Syndrome: Selected references. National Institute for Occupational Safety and Health.

Ward, J. L. (1936). A study of typewriter keyboards. Educational Research Bulletin, 15, 243-246.

Welford, A. T., (1968). Fundamentals of Skill. London: Methuen.

West, C. C. (1945). Measurement of joint motion. Archives of Physical Medicine, 26, 414-425.

West, L. J. (1957). Review of research in typewriting learning with recommendation for training (AFPTRC-TN-57-69). USAF: Air Force Personnel and Training Research Center, Lowry AFT, AD 126400.

Wilson, J. R., and Corlett, E. N. (1990). Evaluation of human work. Bristol, PA: Taylor & Francis.

Wolcott, C. (1920). Keyboards, specification of letters patent, U. S. Patent Number 1,342,244.

Wolstein, S. A. (1986). An experimental study of a six-key handprint chord keyboard. Texas A&M University, Report Number RF. 7053-21.

Appendix A

Participant Screening

This study is being conducted to compare the performances of two fundamentally different keyboards. This study needs to control several parameters to effectively study the use of each keyboard. It is therefore important that each potential subject complete a brief screening procedure. This procedure will help determine if your typing skill meets the criteria set-forth in the study. This screening procedure takes about 25 minutes to complete. Subjects that meet the requirements for participation will be asked to participate in the experiment. Total time expected for the experiment is 5 hours (16, 18 minute 45 second sessions).

As a participant of this screening procedure, and other activity associated with the study, you are entitled to the following rights:
- The experimenter will answer any questions you have concerning procedure associated with any part of the study. You should not sign this, or any other form, until you understand all the terms involved.
- The data collected will be kept confidential and used only for data analysis. Your name will appear nowhere in the study.
- You may terminate participation in this study at any time without penalty.

The research members include:

Peter J. McAlindon,	Graduate Student
Gene Lee, Ph. D., P. E.	Chairman
John E. Biegel, Ph. D., P. E.	Member
Robert Safford, Ph. D., P. E.	Member
N. Clayton Silver, Ph. D.	Member
Kay Stanney, Ph. D.	Member
Chris Bauer, Ph. D., P. E.	Member

If you have any further questions concerning your rights as a participant in this study, please contact Dr. Jose Sepulveda, Program Chairman of Industrial Engineering.

After you have read and agreed to accept the conditions set forth in this document please sign below to consent to participate in the screening procedure described herein.

Signature ______________________ Print Name ______________________

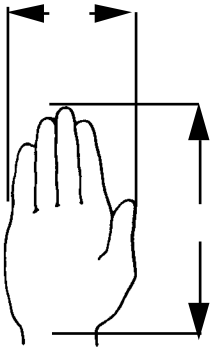
Date ______________________

Appendix B

Screening Test Information

Time starting test:________

Fingers used: LRMI TH All TH IMRL All
'hunt and peck' typing method: Y N
Fingers on home row: Y N
Eyes on: keys screen both %keys %screen
Number of characters typed in 30 second session: characters
GNWP ((characters x 2)/5):______
Musical instruments played (playing): ______________________________
Wrist/Hand Problems:____
Languages spoken fluently:____________________________________



Spatial Test Score: _______ Memory Test Score:_____________

Availability: when are where are the most convenient time for you to participate, if selected (please give specific times)?

	AM	PM
Monday		
Tuesday		
Wednesday		
Thursday		
Friday		
Saturday		
Sunday		

Appendix C

Appendix D

Questionnaire

Please indicate how you personally feel about performing the typing task.

Each of the statements below is something that a person might say about performing a job like typing. You are to indicate your own personal feelings about your experience with the typing task by marking how much you agree with each of the statements.

1. My opinion of myself went up when I performed the task correctly.

1 **2** **3** **4** **5** **6** **7**
Disagree Disagree Disagree Neutral Agree Agree Agree
Strongly Slightly Slightly Strongly

2. Generally speaking, I am very satisfied with performing the typing task.

1 **2** **3** **4** **5** **6** **7**
Disagree Disagree Disagree Neutral Agree Agree Agree
Strongly Slightly Slightly Strongly

3. The typing work I performed was very meaningful to me.

1 **2** **3** **4** **5** **6** **7**
Disagree Disagree Disagree Neutral Agree Agree Agree
Strongly Slightly Slightly Strongly

4. I felt a great sense of personal satisfaction when performing the typing task.

1 **2** **3** **4** **5** **6** **7**
Disagree Disagree Disagree Neutral Agree Agree Agree
Strongly Slightly Slightly Strongly

5. The typing task was usually interesting enough to keep me from getting bored.

1 **2** **3** **4** **5** **6** **7**
Disagree Disagree Disagree Neutral Agree Agree Agree
Strongly Slightly Slightly Strongly

6. Most of the things I had to do to perform the tasks seemed useless or trivial.

1 **2** **3** **4** **5** **6** **7**
Disagree Disagree Disagree Neutral Agree Agree Agree
Strongly Slightly Slightly Strongly

7. My own feelings were not affected much one way or the other by how well I performed the typing task.

1 **2** **3** **4** **5** **6** **7**

Disagree Disagree Disagree Neutral Agree Agree Agree
Strongly Slightly Slightly Strongly

8. I am generally satisfied with the kind of work I performed in the typing process.

1 2 3 4 5 6 7
Disagree Disagree Disagree Neutral Agree Agree Agree
Strongly Slightly Slightly Strongly

9. The feeling of worthwhile accomplishment I got from performing the task.

1 2 3 4 5 6 7
Extremely Dissatisfied Slightly Neutral Slightly Satisfied Extremely
Dissatisfied Dissatisfied Satisfied Satisfied

10. The amount of independent thought and action I could exercise in the tasks.

1 2 3 4 5 6 7
Extremely Dissatisfied Slightly Neutral Slightly Satisfied Extremely
Dissatisfied Dissatisfied Satisfied Satisfied

11. The amount of benefit I will receive from this experience.

1 2 3 4 5 6 7
Extremely Dissatisfied Slightly Neutral Slightly Satisfied Extremely
Dissatisfied Dissatisfied Satisfied Satisfied

12. The amount of challenge in the task.

1 2 3 4 5 6 7
Extremely Dissatisfied Slightly Neutral Slightly Satisfied Extremely
Dissatisfied Dissatisfied Satisfied Satisfied

13. The overall quality of supervision I received while performing these tasks.

1 2 3 4 5 6 7
Extremely Dissatisfied Slightly Neutral Slightly Satisfied Extremely
Dissatisfied Dissatisfied Satisfied Satisfied

14. The level of mental effort required to perform the tasks.

1 2 3 4 5 6 7
Extremely Dissatisfied Slightly Neutral Slightly Satisfied Extremely
Dissatisfied Dissatisfied Satisfied Satisfied

15. Remembering the locations of the keys was

1 2 3 4 5 6 7
Extremely Moderately Slightly Neutral Slightly Moderately Extremely
Difficult Difficult Difficult Easy Easy Easy

16. Becoming familiar with the keyboard was

1 2 3 4 5 6 7

Extremely Moderately Slightly Neutral Slightly Moderately Extremely
Difficult Difficult Difficult Easy Easy Easy

---

17. The movement required to activate a key was

1 2 3 4 5 6 7
Extremely Moderately Slightly Neutral Slightly Moderately Extremely
Difficult Difficult Difficult Easy Easy Easy

---

18. Using the keyboard was

1 2 3 4 5 6 7
Extremely Moderately Slightly Neutral Slightly Moderately Extremely
Difficult Difficult Difficult Easy Easy Easy

---

19. During each session, muscle fatigue in the hands was

1 2 3 4
High Moderate Slight None

---

20. During each session, muscle fatigue in the wrist was

1 2 3 4
High Moderate Slight None

---

21. During each session, muscle fatigue in the arms was

1 2 3 4
High Moderate Slight None

---

22. **For Keybowl users only**: The Keybowl is a viable alternative to typing

1 2 3 4 5 6 7
Disagree Disagree Disagree Neutral Agree Agree Agree
Strongly Slightly Slightly Strongly

---

23. **For Keybowl users only**: I would recommend the Keybowl to other typists

1 2 3 4 5 6 7
Disagree Disagree Disagree Neutral Agree Agree Agree
Strongly Slightly Slightly Strongly

Appendix E

ANOVA Summary Table for Flexion and Extension Movements

Source	DF	SS	MS	F	P
[Between Subjects]					
Keyboard (K)	1	32124.99	32124.99	58.34	<0.0001

Gender (G)	1	5791.21	5791.21	10.52	<0.0001
K x G	1	2987.85	2987.85	5.43	<0.0280
SS/(K x G)	26	14316.715	550.64		
[Within Subjects]					
Stage (ST)	1	1576.22	1576.22	19.84	<0.0001
STx K	1	923.48	923.48	11.62	<0.0020
SS/(K x G) x ST	26	2066.35	79.47		
Hand (H)	1	1025.02	1025.02	6.02	<0.0200
SS/(K x G) x H	26	4427.17	170.27		
Session (S)	7	345.62	49.37	2.93	<0.0174*
SS/(K x G) x S	182	3070.405	16.87		
ST x S	7	426.35	60.90	3.87	<0.0007*
SS/(K x G) x ST x S	182	2861.366	15.72		

* Significance level for Box Epsilon

ANOVA Summary Table for Ulnar and Radial Movements

Source	DF	SS	MS	F	P
[Between Subjects]					
Keyboard (K)	1	2602.43	2602.43	15.99	<0.0005
Gender (G)	1	891.88	891.88	5.48	<0.0275

SS/(K x G)	26	4230.67	162.71		
[Within Subjects]					
Stage (ST)	1	478.59	478.59	39.74	<0.0001
ST x K	1	150.52	150.52	12.50	<0.0020
SS/(K x G) x ST	26	313.11	12.04		
Hand (H)	1	640.66	640.66	10.37	<0.0035
H x G	1	364.03	364.03	5.89	<0.0260
H x G x K	1	281.85	281.85	4.56	<0.0423
SS/(K x G) x H	26	1606.84	61.8		
H x ST	1	38.24	38.24	6.63	<0.0165
H x ST x G	1	34.67	34.67	6.01	<0.0215
H x ST x G x K	1	45.48	45.48	7.88	<0.0095
SS/(K x G) x H x ST	26	149.97	5.76		
S (S)	7	81.60	11.65	3.56	<0.0195*
SS/(K x G) x S	182	595.84	3.27		

* Significance level for Box Epsilon

ANOVA Summary Table for Performance (Gross Words Per Minute)

Source	DF	SS	MS	F	P
[Between Subjects]					
Keyboard (K)	1	33056.37	33056.37	47.55	<0.0001
Gender (G)	1	3330.50	3330.50	4.79	<0.0380

SS/(K x G)	26	18076.38	695.24		
[Within Subjects]					
Stage (ST)	1	16758.27	16758.27	290.92	<0.0001
ST x K	1	1247.75	1247.75	21.66	<0.0001
ST x K x G	1	651.39	651.39	11.31	<0.0025
SS/(K x G) x ST 26	1497.7	57.6			
Session (S)	7	2492.06	356.00	105.27	<0.0001*
SS/(K x G) x S	182	615.49	3.38		
ST x S x K	7	68.76	9.82	5.58	<0.0005*
SS/(K x G) x ST x S	182	320.57	1.76		

* Significance level for Box Epsilon

ANOVA Summary Table for NASA-TLX

Source	DF	SS	MS	F	P
[Between Subjects]					
Keyboard (K)	1	4680.8	4680.8	1.78	>0.05
Gender (G)	1	5822.53	5822.53	2.22	>0.05

SS/(K x G)	26	68199.75	2623.067		
[Within Subjects]					
Stage (ST)	1	5820.47	5820.47	18.82	<0.0002
SS/(K x G) x ST	26	8014.52	308.25		
Session (S)	7	6545.86	935.12	3.56	<0.0001
S x K	7	2512.02	358.86	4.66	<0.0001
S x K x G	7	1442.63	206.09	2.67	<0.0120
SS/(K x G) x S	182	14030.08	77.08		

ANOVA Summary Table for Error Analysis

Source	DF	SS	MS	F	P
[Between Subjects]					
Keyboard (K)	1	37482.22	37482.22	10.13	<0.0040
Gender (G)	1	9577.57	9577.57	2.59	>0.05
SS/(K x G)	26	96204.52	3700.17		

[Within Subjects]

Stage (ST)	1	13757.38	13757.38	14.15	<0.0010
SS/(K x G) x ST	26	25283.37	972.43		
Session group (SG)	1	2464.64	2464.64	16.87	<0.0005
SG x K	1	946.8	946.8	6.48	<0.0175
SS/(K x G) x SG	26	3797.58	146.06		
Letter (L)	15	8980.49	598.70	4.46	<0.0006*
L x K	15	10099.84	673.32	5.02	<0.0002*
SS/(K x G) x L	390	52348.58	134.22		
ST x L	15	3681.73	245.44	4.19	<0.0019*
ST x L x K	15	4153.89	276.93	4.73	<0.0007*
SS/(K x G) x ST x L	390	22848.83	58.58		
ST x SG x L	15	1072.13	71.47	3.00	<0.0089*
ST x SG x L x K	15	917.88	61.19	2.57	<0.0221*
SS/(K x G) x ST x SG x L	390	9278.35	23.79		

* Significance level for Box Epsilon