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Chapter 54

Keys and Keyboards

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54.1 Introduction

Keyboards have been around for over 100 years and are in widespread use both on typewriters and as input devices to computers. Early refinements of the typewriter keyboard aimed at improving its mechanical action so that it would operate more smoothly with fewer malfunctions. Later work focused on improving typing speed and accuracy.

This chapter describes keyboard design factors that affect skilled typing and data entry. The information presented should apply equally well to typewriter and computer keyboards. Some data also apply to telephones and other specialized keypads used for data entry tasks.

54.2 Keyboard Layouts

The locations of letters and numbers on keys has been a matter of research, theory, debate, contests and patent applications since the appearance of the first conventional typewriter keyboard. Although other typewriters existed previously, the design patented in 1868 by Sholes, Glidden, and Soule was the first to include many of the characteristics of modern typewriters (Yamada, 1980). The letters originally had an alphabetic arrangement.

54.2.1 The Standard (QWERTY) Layout

Fast typists ran into trouble with the early design of the Sholes keyboard because the typebars of successive keystrokes would interfere with each other. The current QWERTY layout (named for the top left-most row of letters) increased the spacing between common pairs of letters to reduce the frequency of jamming sequentially struck typebars[1]. Touch typing on the Sholes keyboard was not common until around 1900 (Yamada, 1980). The first patent showing the QWERTY layout appeared in 1878 (Cooper, 1983; Noyes, 1983b). There have been several attempts to improve the keyboard layout by developing non-QWERTY arrangements.

54.2.2 The Dvorak Simplified Keyboard Layout

The most well known of these attempts was the Dvorak Simplified Keyboard (known as DSK). August Dvorak received a U.S. patent for his design in 1936. Dvorak designed his layout using principles of time-and-motion study and scientific measurement of efficiency (Dvorak, 1943). Dvorak assumed for his analyses ten-fingered touch typing.

The principles underlying Dvorak's layout included assumptions such as simple motions are easier to learn and perform rapidly than more complex motions, and rhythmic motions are less fatiguing than erratic ones. With the DSK layout, typists use the right hand more than the left, with fingers assigned proportionate amounts of work. Almost 70% of the typing is on the home row. The placement of vowels and frequently-used consonants on opposite halves of the keyboard increases the frequency of two-handed typing sequences[2].

Many experiments, field trials and analytical studies have compared the DSK with the QWERTY arrangement. Dvorak conducted some of his own tests with reportedly positive results. Five other studies comparing DSK and QWERTY keyboards appear below.

The Navy Department Study

In the 1940s, the Navy Department compared two groups of typists who received on-the-job training (U.S. Navy Department, 1944a, 1944b). The first group consisted of QWERTY-trained typists who learned the DSK layout. The second group of QWERTY typists received additional training on the standard keyboard.

Increases in typing speeds and decreases in error rates were higher for the DSK group. However, the gain in net words per minute (nwpm) was not statistically significant. Also, there were pre-existing differences between the two groups because the DSK typists initially were faster on QWERTY than the other group.

The Navy Department report did not focus on the final nwpm, but instead described differences between the groups in terms of *percentage gain in nwpm as a function of the number of hours of additional training*. In measuring this learning rate, the researchers used zero as the baseline for the DSK group because they had never used DSK before. The QWERTY group baseline was their typing rate before additional training. The use of different baselines affected the calculation of learning rate. Also, the initial learning rate for the DSK group could have been quite high because some previously learned typing skills (such as finger movements) would be relevant for learning DSK. Later performance might not show such a rapid rate of learning.

Navy Department researchers also calculated the costs and benefits of retraining compared to additional QWERTY training. However, the cost figure was "corrected" by subtracting the value of increased production during the latter part of the retraining period *for the DSK group only*. That is, once typists in the DSK group exceeded their original QWERTY typing rates, the increase in production received a dollar value. The correction factor was the number of hours each typist worked at greater than 100% of QWERTY typing speed multiplied by the individual's hourly wage. Without this correction factor, the average cost of retraining was actually cheaper per hour for additional QWERTY training ($1.27/hour DSK and $0.90/hour QWERTY).

The Navy Department report concluded with highly favorable statements about DSK retraining and recommendations for implementing such retraining. The following facts invalidate this conclusion: a) differences in final typing performance were not statistically significant; b) measures of learning rates unfairly favored the DSK group; and c) calculations of costs and benefits unfairly favored the DSK.

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[1] There are other theories about how QWERTY came into existence. For a summary, see Noyes (1983). Alleviation of typebar jamming problems was the explanation appearing most frequently in the literature.

[2] The Dvorak measurements assume English text. For recent applications of Dvorak-like principles to the design of non-English keyboards, see Kan, Sumei, and Huiling, 1993; Lin, Lee, and Chou, 1993; and Marmaras and Lyritzis, 1993.

The Strong Study

Strong (1956) conducted his study for the U.S. General Services Administration. Strong trained QWERTY typists on DSK keyboards until they reached their previous QWERTY typing performance levels. This took an average of about 28 days. In the second part of the experiment, the DSK group received additional instruction time to increase their speed and accuracy on DSK. A comparable group of QWERTY typists began the experiment in the second half and received only this additional training (but on QWERTY). After training, the QWERTY group performed better on typing tests than the DSK group (Alden, Daniels, and Kanarick, 1972; Noyes, 1983b). Strong concluded that there were no advantages to the DSK and that "brush up" training on QWERTY was more effective (Yamada, 1980).

Other researchers have questioned the Strong report. Some tried to obtain the original experimental data for re-evaluation, but learned that all the data had been destroyed. There has been speculation that the study unfairly favored QWERTY (Noyes, 1983b) and that Strong himself was "hardly an unbiased investigator" (Yamada, 1980, p. 188). Regardless of whatever motivated Strong to write such a report, it clearly was a major blow to public acceptance of DSK and the adoption of DSK by the U.S. government (Cassingham, 1986; Yamada, 1980).

Kinkead's Simulation

It is difficult to conduct a fair experiment to compare DSK and QWERTY due to QWERTY's widespread use. Previous experience could affect both DSK retraining and additional QWERTY training in unknown ways. To circumvent the methodological difficulties of training and retraining typists on each keyboard, Kinkead (1975) collected data on the times required for the fingers to type each possible sequence of two letters (called a "digram" or "digraph") on the QWERTY keyboard. The second part of the analysis was to obtain the frequency with which each digraph occurs in English.

Kinkead (1975) assumed that the time to make a particular finger motion ("keystroke time") would be the same for both DSK and QWERTY. That is, the keys and rows have the same arrangement on both keyboards, so they require the same finger motions. The only difference between layouts was the assignment of letters to the key locations and thus the frequency of use for each finger motion. Kinkead used the sum of all "digraph frequency x keystroke time" values to estimate the typing speed for each keyboard layout.

The results of this analysis indicated that, at best, DSK is 2.3% faster than QWERTY. (This value of 2.3% appears below his table of calculations; in the text, the number is 2.6%.) There are some minor discrepancies between these values and calculations based on the numbers in Kinkead's (1975) report. For example, using the same numbers as Kinkead, the advantage of DSK over QWERTY could be either 3.1% or 3.2%, depending on the use of Kinkead's first (155 msec/keystroke) or second (151 msec/keystroke) estimate of average keystroke time.

Another difficulty in interpreting the Kinkead (1975) data stems from the effect of context on typing speed and the "leveling effect". The context surrounding a character affects the speed of typing that character. If the size of the affecting context is larger than a digraph, then Kinkead's estimates might not be accurate. Gentner (1983) reported that the size of the effective context is two letters before and one character after the currently typed character. Calculations for trigraphs (three-letter sequences) show that when a particularly slow keystroke occurs, other keying sequences surrounding it also slow down. Fast keying sequences tend to speed up surrounding keystrokes (Hiraga, Ono, and Yamada, 1980). This tendency to maintain a constant typing speed from one keystroke to the next is the leveling effect. The context and leveling effects could explain why Kinkead obtained such a low estimate for DSK's advantage over QWERTY, because the analysis used digraphs only.

A Computer Simulation

Norman and Fisher (1982) performed another comparison of DSK and QWERTY using "a computer simulation of the hand and finger movements of a skilled typist" (p. 154). Their model accounted for the context effect because it "allows for the simultaneous movement of the fingers and hands toward different letters of the word being typed, thus capturing the parallel, overlapping movements seen in high-speed films of expert typists" (p. 515). They calculated that DSK provides about a 5.4% advantage in typing speed over QWERTY. Application of the model resulted in a typing rate of about 58 words per minute (wpm) for DSK compared to about 56 wpm for QWERTY.

This study addressed some of the criticisms of the Kinkead (1975) report. The computer model took into account more than just digraph frequencies in determining speed of finger motions. Note, however, that both simulations (Kinkead, 1975; Norman and Fisher, 1982) address only typing speed of expert typists.

An Automated Search for the Best Key Layout

Noel and McDonald (1989) used an artificial intelligence search procedure to discover the best possible key layout for the standard keyboard configuration. Their algorithm used the typing model developed by Norman and Fisher (1982) to direct the search. Their program considered 50,000 keyboard layouts from the first to the final iteration of the search. The results indicated that the DSK was about 10% better than QWERTY, and that the best possible layout was 1.2% better than DSK.

Conclusions

Most studies have confirmed that DSK is faster than QWERTY. However, there is disagreement about the size of the difference between the two keyboard layouts. Earlier accounts claimed that DSK was from 15% to 50% faster than QWERTY (Yamada, 1980). More recent calculations give much smaller numbers, ranging from 2.3% to 17% (Kinkead, 1975; Norman and Fisher, 1982; Yamada, 1980). Because the best design their search procedure could turn up was only 1.2% better than the DSK, the results of Noel and McDonald (1989) suggest that it would be fruitless to attempt to develop a layout in the standard keyboard configuration significantly superior to the DSK.

Because there are so many unknowns (such as how long it will take a particular typist to retrain), a switch to DSK would probably not provide a practical improvement in productivity. With an estimated 5 to 10% increase in output over QWERTY (Noel and McDonald, 1989; Norman and Fisher, 1982), the switch might be cost effective for some typists, but essentially worthless for most. For example, a typist with an average speed of 50 wpm would, after complete retraining, produce 52.5 to 55 wpm. At roughly 800 words per single-spaced page, this hypothetical retrained typist, typing nonstop for eight hours per day, would increase production from about 30 pages per day up to 31.5 to 33 pages per day. Also, a typist trained on QWERTY can easily transfer his or her skill to any other standard keyboard, but a typist trained on DSK could not.

54.2.3 Alphabetical Keyboards

Another method of designing a keyboard is to place letters on the keys in alphabetical order. Such a layout has appeared on some children's toys, on a stockbroker's quotation terminal, on some portable data devices, and sometimes appears as the default on-screen keyboard for some touchscreen applications.

Research Comparing QWERTY and Alphabetical Keyboards

Hirsch (1970) tested one group of non-typists on QWERTY and another group on an alphabetically arranged keyboard. After seven hours of practice, the QWERTY group improved their typing speed from 1.47 to 1.99 keystrokes per second. The alphabetical group, however, did not even reach their pre-experimental QWERTY typing rates (1.47 keystrokes per second for QWERTY compared to 1.11 for alphabetical).

Michaels (1971) expanded on the work of Hirsch by including people with a broader range of typing skills, ages and backgrounds. Results showed that both the high- and medium-skill groups were significantly faster on QWERTY, while the low-skill group showed no significant difference in typing speed on the two keyboards. Also, skilled typists were faster at keying numerical sequences on QWERTY than on the alphabetical keyboard even though the number keys were exactly the same on both typewriters, a result that might have been due to a leveling effect.

Norman and Fisher (1982) tested non-typists on four different keyboards: QWERTY, Alphabetical-Horizontal (letters A through Z arranged from left to right starting with the letter keys at the upper left of the keyboard), Alphabetical-Diagonal (with letters arranged from top to bottom and then from left to right starting at the upper left of the keyboard), and a Random keyboard (letters assigned to letter keys at random). Typing was more than 65% faster on QWERTY than on any of the other layouts. Statistical tests revealed that the first three keyboards were all significantly better than the random arrangement, and that QWERTY was better than both alphabetical layouts (which were not significantly different).

A study of small keypads for an enhanced telephone application compared QWERTY and alphabetical layouts (Francas, Brown, and Goodman, 1983). The size of the keypads limited typing to a one- or two-finger strategy. The 20 participants in the study had keyboard experience ranging from those who had not used a keyboard in the previous year to those who used a keyboard daily. The average time for entering sentences was 54.4 seconds for QWERTY and 97.5 seconds for the alphabetical layout. The typists in the study strongly preferred the QWERTY to the alphabetical layout. The advantage for QWERTY did not appear to be a function of the typists' experience.

Recent interest in portable data devices and on-screen keyboards for touch screens have led to additional research in the evaluation of nonstandard alpha-

betic arrangements. Lewis, Kennedy, and LaLomia (1992) used a cost function based on Fitts' Law[3] and English digraph frequencies to evaluate (1) the alphabetical arrangement created by replacing the QWERTY letters with alphabetically-sequenced letters and (2) the alphabetical arrangement created by placing the letters in a roughly 5 x 5 key matrix (with "Z" placed just outside the square matrix, and (3) the standard QWERTY arrangement given expert (completely learned) typing with a stylus or a single finger (hereafter referred to as stylus-typing). (Note that the problems associated with Kinkead's (1975) use of digraphs are primarily a consequence of typing with ten fingers, and do not apply to typing with a stylus or one finger.) For expert stylus-typing, the cost function predicted that the conventional alphabetic arrangement would be 3% slower than QWERTY, but that the roughly square alphabetic arrangement would be about 13% better than QWERTY.

Because one assumption of the cost function was expert performance, Lewis (1992) studied initial user preference and performance with the layouts. Although predicted expert performance is important in selecting a typing-key layout, it is also important to evaluate users' initial performance with and preference for competing layouts. This is especially true if it is unlikely that users will work with a device enough to develop an expert level of performance. In the study, 12 participants used a stylus to tap keys on paper models of the layouts to type four sentences. All the participants had previous experience with the QWERTY layout, and had self-reported typing speeds ranging from 10 to 65 wpm. The participants (who were at this point, non-expert stylus-typists) performed better with and preferred the QWERTY layout. Thus, initial performance differed from predicted expert performance, with initial performance favoring the QWERTY layout. Even though this study evaluated only initial performance, stylus typing with the square alphabetic arrangement was significantly faster than that for the conventional alphabetic arrangement, as predicted by the user model. There are no data on how long a person would have to practice with these nonstandard layouts to achieve expert performance.

Coleman, Loring, and Wiklund (1991) also found an advantage for a touch-screen QWERTY arrangement over an alphabetical arrangement using a matrix seven keys across and four keys high. Their experiment, however, had a confounded variable because only the alphabetical layout had an embedded numeric pad, making it slower for typing numbers. MacKenzie et al. (1994) compared a touch-screen QWERTY arrangement with an alphabetical arrangement 13 keys across and 2 keys high. Fifteen participants with prior QWERTY experience typed sentences (lower case only, no punctuation) significantly faster with the QWERTY layout and significantly preferred the QWERTY. Quill and Biers (1993) had 24 participants (both touch and non-touch typists) use a mouse and cursor keys to select characters from an on-screen QWERTY layout, a 3-row (QWERTY-like) alphabetical arrangement, and a 1-row alphabetical arrangement to type a mixture of words and nonwords, presented one at a time. The participants significantly preferred the QWERTY layout to both alphabetical arrangements, with no significant difference between the alphabetical layouts. Input with the mouse was always faster than with the cursor keys. Using the mouse, the typing speed results were the same as the preference results. For the cursor keys, typing speeds with the QWERTY and 1-row alphabetical arrangements were not significantly different, but both were significantly faster than the 3-row, standard alphabetical arrangement.

Conclusions

Alphabetically arranged keyboards (apparently regardless of specific arrangement) provide no advantages over QWERTY, even for unskilled typists using a reduced-size keypad (Francas et al., 1983), or for typists restricted to using a stylus or mouse (Lewis, 1992; MacKenzie et al., 1994; Quill and Biers, 1993). Performance on QWERTY might be better than alphabetical keyboards because the QWERTY arrangement is not random, reducing the difficulty of search. Another possible explanation is that most people, even inexperienced typists, have some experience using a QWERTY keyboard. Overall, the evidence suggests that in most situations designers should provide a QWERTY rather than an alphabetical layout.

54.2.4 Other Keyboard Layouts

A few researchers have developed nonstandard layouts in nonstandard arrangements for special purposes. Getschow, Rosen, and Goodenough-Trepagnier (1986) used an artificial intelligence search procedure (the "greedy"

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[3] Fitts' Law (Fitts, 1954) is a model of human performance that describes the time required to touch a target accurately. Specifically, Fitts' Law states $\underline{MT} = \underline{a} + \underline{b}\log_2(2\underline{A}/\underline{W})$, where $\underline{MT}$ is movement time, $\underline{A}$ is the amplitude (distance to the target), $\underline{W}$ is the size (width) of the target, and $\underline{a}$ and $\underline{b}$ are empirically determined constants. The law essentially states that increasing $\underline{A}$ or decreasing $\underline{W}$ increases movement time in a specific and definable way. See Welford (1976) for a detailed description of this and other versions of Fitts' Law.

algorithm) to develop a layout that minimized the weighted average distance between English digraphs (with keys occupying a roughly 5 x 5 key square matrix). Theoretically, this should be the best layout for an expert typing with a stylus or a single finger, but Getschow et al. did not perform any user testing with the layout.

Lewis et al. (1992) used a path-analysis program to design a minimum-distance layout similar to that developed by Getschow et al. (1986). Using a cost function based on the frequency of English digraphs and Fitts' Law, Lewis et al. estimated that, for stylus typing by a highly practiced expert, this minimum-distance layout would be 27% faster than a QWERTY layout. Using the same assumptions (highly practiced stylus typing with the layout), Lewis (1992) estimated that a layout based on that developed by Getschow et al. would be 31% better than QWERTY.

The cost function of Lewis et al. (1992) predicts expert stylus typing performance, but is not applicable to initial, nonexpert typing. Because a designer might consider a nonstandard arrangement for situations in which typists might not acquire an expert level of skill, it is important to understand initial user performance with such layouts. In an assessment of initial user preference and performance with the layouts (Lewis, 1992), however, 12 typists using paper models of the layouts significantly preferred and performed better with the QWERTY layout (and had their second-best performance with a 5 x 5 alphabetical arrangement). There was no performance difference between the Lewis et al. and Getschow et al. layouts, but participants significantly preferred the layout by Lewis et al.

Matias, MacKenzie, and Buxton (1993) developed a one-handed keyboard called the Half QWERTY, designed to take advantage of a typist's existing skill with the QWERTY layout. Taking advantage of cross-hand skill transfer, the Half QWERTY has two character functions on each key from the left half of the QWERTY layout, with a mirror image of the right half placed on the left half. For example, the Q key is also the P key; the T key is also the Y key; the B key is also the N key. Typists press a key as usual to get the normal letter associated with the key, but press and hold the space bar to get the alternate, mirror-image letter. Ten participants learned to use the Half QWERTY as they typed sentences presented by a computer program for ten sessions, with each session lasting about an hour. The average typing speed at the end of the first session was 13.2 wpm with 16% errors. The average speed after the tenth session was 34.7 wpm with 7.4% errors. Subjects reached 50% of their two-handed typing speed after about eight hours.

Montgomery (1982) proposed a wipe-activated capacitive keyboard. The "keyboard" is a flat tablet that the fingers glide across or wipe to create characters. To take advantage of the wiping motion, Montgomery also developed a new character layout to enable the input of many small words with a single wiping motion. An alternative method of operation is to use a stylus to interact with the keyboard. Because it has no moving parts, this device can be almost any size. This keyboard has undergone no tests other than analyses comparing number of wipes to number of keystrokes required on standard keyboards.

Conclusions

The concepts discussed in this section are interesting, and might have application under certain unusual circumstances. However, designers should always assess an alternative layout against a QWERTY layout designed to fit in the same physical dimensions as the alternative before committing to an alternative design, especially if it is not reasonable to expect users of the keyboard to become expert.

54.2.5 Keyboard Layouts: Conclusions

Given the structure of the standard keyboard (three rows of letters with an upper row of numbers), there are many ways to arrange the alphabetic keys. By starting from an alphabetically ordered arrangement, then rearranging keys to reduce type bar jamming, the inventors of the standard keyboard created the QWERTY layout. Even if their intention was to reduce typing speed as well as reduce jamming, separating commonly co-occurring letters increases the frequency with which a typist strikes characters with fingers between hands (from hand to hand). Analysis of skilled typists has shown that typing with fingers on alternate hands is faster than typing with fingers on a single hand (which is faster than typing with a single finger) (Cooper, 1983). Thus, the inventors of the standard keyboard seem to have accidentally created a layout that allows skilled touch typists to type with about 90% of the speed theoretically attainable with the best possible layout for touch typing (Noel and MacDonald, 1989).

Most recent estimates suggest that Dvorak's design closed the gap to about 95 to 99% of the maximum possible touch-typing speed. To date, no other keyboard layout has received more attention than DSK as an alternative to QWERTY, but it appears that most typists do not believe that the relatively minor benefit of learning the DSK would overcome the costs. Other

than as an academic exercise, any further redesign of the QWERTY layout for touch typing appears to be a fruitless effort, a conclusion consistent with the ANSI/HFS 100-1988 standard's recommendation to use the QWERTY layout for typing keyboards (Human Factors Society, 1988).

A remarkable finding from the more recent evaluations that have compared the QWERTY layout with other layouts for reduced-size devices and on-screen keyboards (both alphabetically ordered and digraph ordered) is the consistent superiority of the QWERTY layout, at least in the short term. Clearly, the first choice for designers providing a keyboard or typing layout for almost any purpose is the QWERTY layout.

54.3 Data-Entry Keypads

In addition to the main alphanumeric section, most computer keyboards have a separate numeric keypad for data entry. Also, use of push-button telephones as remote terminals to computers continues to rise (a phenomenon originally reported by Bayer and Thompson, 1983; Hagelbarger and Thompson, 1983). This section considers the design of keypads for telephone and other applications.

54.3.1 Layout of Numbers and Letters

Lutz and Chapanis (1955) tested six key configurations to determine where people expected each letter and number to appear on ten-button keysets for use by long-distance telephone operators. The key arrangements were two horizontal rows of five keys, two vertical rows of five keys, or three rows of three keys with a single key placed at the top, bottom, left or right of the block of nine keys. In general, people placed letters and numbers on keys in the same order as they read text (that is, from left to right and from top to bottom) regardless of the key configuration. When numbers were already on the keys: a) people consistently placed letters on the keys from left to right and from top to bottom when the numbers had that arrangement; and b) if the arrangement of numbers was not from left to right and top to bottom, about half of the people placed the letters to be consistent with the ordering of the numbers, and the other half persisted in arranging the letters from left to right and from top to bottom. The most frequent number arrangement was that found on the majority of modern U. S. telephones.

Detweiler, Schumaker and Gattuso (1990) asked telephone company employees to assign by memory the alphabetic letters of the telephone keypad (which does not list "Q" or "Z") on a blank representation of the keypad. Only 18% of these subjects were able to correctly place the letters on the keys with 100% accuracy on the first trial. After subsequent training, however, 72% of the participants achieved 100% accuracy. Detweiler et al. concluded that despite the thousands of interactions that people have with the telephone keypad, few people really have learned the mappings between the letters and keys.

Other studies have compared performance with the telephone layout (1, 2, 3 across the top with 0 at the bottom) and the common calculator layout (7, 8, 9 across the top). Conrad and Hull (1968) asked housewives to enter numeric codes and found the telephone layout was superior in both speed and accuracy. Paul, Sarlanis, and Buckley (1985) tested air traffic controllers and found that the telephone layout was better for entry of letters and mixed (letter and number) data, but that performance was the same for entry of numbers only.

A related study (Goodman, Dickinson, and Francas, 1983) used a simulation methodology to determine the best layout of keys for Telidon (Canadas Videotex system) keypads. They tested both a horizontal (1 through 0 in a single row) and a telephone arrangement. Speed and accuracy were slightly better on the telephone layout in a reaction-time task. However, differences in more realistic performance were not statistically significant. Preferences were strongly in favor of the telephone arrangement for a problem-solving task that simulated expected use of the Telidon system, but were slightly in favor of the horizontal arrangement for the reaction-time task.

Magyar (1986a) compared numeric entry throughput and error rate by typists performing an extended numeric entry task (5-digit numbers) using either the keyboard's horizontal top row of numbers or the separate 10-key calculator keypad. Half of the test participants had experience using a 10-key numeric keypad. The typists worked as they normally would with the two configurations, using both hands to enter numbers from the top row and one hand to enter numbers with the calculator keypad. Although the participants tended to commit fewer keying errors with the 10-key keypad, there were no significant differences between overall speed and accuracy with the two methods. Reanalysis of the data to evaluate performance differences attributed to user experience revealed that keying time for experienced keypad users was significantly faster on the keypad than with the top row. Keypad entry speed for experienced participants was faster than that by the inexperienced operators. Although keying speed for in-

experienced users was faster with the top-row keys than with the numeric keypad, overall speed and accuracy for the top-row keys were equivalent for both groups. Similar to the findings of Goodman et al. (1983), the participants strongly preferred using a calculator keypad for the numeric entry task rather than the top row keys, citing increased speed and accuracy as the primary reasons for their preference.

Conclusions

The design and use of data-entry keypads depends to a great extent on the keying task required. For numeric and mixed input, the telephone layout is slightly superior to the calculator layout, especially for people who are not familiar with calculators or adding machines. Experienced keypad users who need to perform extensive numeric entry tasks appear to benefit from having a separate numeric-entry keypad on their keyboards. These data and conclusions are consistent with the ANSI/HFS 100-1988 standard's recommendation to provide a numeric keypad when the primary task includes the entry of numeric data, and to consider the application when choosing the calculator or telephone layout (Human Factors Society, 1988).

54.3.2 Alphanumeric Entry with Telephone Keypads

Because telephone keypads contain more than one letter on each key, their use for alphanumeric data entry requires a strategy for designating which letter goes with each keypress (or sequence of keypresses). Procedures for differentiating letters located on the same key are "disambiguation" techniques. Davidson (1966) suggested using the two extra keys on push-button telephones as control keys. The left (*) button would indicate the first letter, the right (#) button would indicate the third letter, and a keypress without a control key would indicate the middle letter. Francas, Brown, and Goodman (1983) compared Davidson's suggested method with both a miniature QWERTY keypad and an alphabetically arranged one. For entering alphabetic data, the telephone keypad with left and right control keys was significantly slower than either the QWERTY or alphabetical keysets, but accuracy was the same for all entry methods. The authors concluded that the telephone keypad was not suitable for entering letters in their application. However, for tasks that primarily require accuracy and have severe space limitations (or simply require the use of a standard telephone), the telephone keypad with control keys might be acceptable.

A particular problem with using the standard telephone keypad for alphabetic data is the absence of the letters "Q" and "Z" as well as other punctuation marks such as hyphens or apostrophes. Marics (1990) examined the ways that users would attempt to enter special names (e.g. O'Brien or Razzler) using the traditional telephone keypad. Results did not indicate a clearly preferred method of entering the Q, Z, and Hyphen. About one third of the subjects chose a non-alphabetic character key (such as "*") for these letters while another third chose the key where the letter should have been (for example, by pressing "7" (PRS) for "Q"). Eighty percent of the participants ignored (did not enter) characters such as apostrophes. Thus, there is no clearly superior method for assigning missing alphabetic and punctuation characters to the numeric and non-numeric keys of the standard telephone keypad, and a standard has yet to emerge.

A study of data entry for aircraft cockpits compared three keypads designed for one-handed keying (Butterbaugh and Rockwell, 1982). Task performance was fastest and most accurate with a keyboard having separate keys for each letter and number. However, further analyses showed that this difference was mainly due to the fact that the two other multifunction keypads required more keystrokes to enter each letter. Raw keypressing speed (but not letter input) was fastest with a telephone layout with letters assigned horizontally to the number keys. Butterbaugh and Rockwell recommended using a full keyboard if at all possible. If a space requirement forced the use of a smaller keypad, they suggested a telephone layout with letters assigned from left to right and from top to bottom. They also recommended using three control keys (for left, middle, and right characters) located in the top row of keys.

Brown and Goodman (1983) compared several methods of entering alphabetic text through a telephone keypad by employing various arrangements of control keys located above the telephone keypad. In one condition, subjects entered letters by pressing a single control key, then pressing the telephone key with the desired letter on it the number of times corresponding to the position of the letter in its group of three. In the two-control key arrangement, participants pressed either the "left control" key (for the first of the triplet letter per key) or the "right control" key (for the third letter) or both control keys (for the second letter) before each letter, then pressed the key with the selected letter. In the three-control key condition, letters were selected by pressing the "left", "center", or "right" control key, then the number key with the given

letter. Alphabetic data entry using the two-control key arrangement was significantly faster and showed significantly greater improvement with practice than either the single-key or the three-control key arrangements, which did not differ in entry speed. Accuracy across all three conditions was comparable, however, and there were no significant differences in error rates. Although the two-control key method appeared superior to the three-key method recommended by Butterbaugh and Rockwell (1982), the authors concluded that the slow speeds of less than 10 wpm for all three of the arrangements were clearly impractical for tasks requiring extended text entry.

Detweiler, Schumacher, and Gatusso (1990) evaluated five different strategies for entering alphabetic letters (but not mixed alphanumeric data) from a telephone keypad. Because some methods (such as the "Repeat-Key" method) specified a purely cognitive strategy of entering alphabetic data (to press the key containing the letter the number of times corresponding to its ordinal position on the key), but others (such as the "Modal-Position" method) specified the use of "control" keys (to press the *, 0, or # key to designate the first, second or third letter on the next numeric key pressed), it is difficult to compare or generalize these performance findings to other studies that employed separate or additional control keys to allow for mixed alphanumeric entry on the same telephone keypad. Although there were few statistically significant differences in performance among the methods investigated, Detweiler et al. recommended (with qualifications) the Repeat-Key method. As they pointed out, however, the Repeat-Key method does not provide a clear way to enter the letters or other special characters not represented on the telephone keypad and requires users to pause for a detectable period of time between the entry of letters that appear on the same key.

Alternative approaches to disambiguation have investigated methods that do not require the user to learn a particular cognitive strategy or to use separate control keys on the keypad. Instead, a computer system incorporates statistical techniques to "predict" the word or name that a user is entering by examining unique key combinations, consulting an internal dictionary, and using trigram-based transistional probabilities to generate the most likely word for a combination of keystrokes (Minneman, 1985). Current models using statistical disambiguation techniques can achieve 90% correct prediction rates, but the extent to which the errors affect overall performance is unknown (Foulds, Soede, Balkom, and Boves, 1987). Because statistical disambiguation is not perfect, telephone keypads with statistical disambiguation systems need either (1) a key to allow users to signal disambiguation errors or (2) voice prompts to guide users through structured transactions, including the identification of disambiguation errors[4].

Conclusions

For the entry of letters or mixed alphanumeric data, telephone (and other small multifunction) keypads are no match for even reduced-size QWERTY or alphabetic keyboards. If speed is not important, but accuracy and space are critical, then a telephone keypad might be acceptable for limited data entry. The telephone keypad appears to be acceptable (but not optimal) for use as a remote terminal. Using a telephone keypad for limited alphanumeric entry will require adequate labeling of keys (or user instruction) to allow the entry of all the letters of the alphabet and a means for performing character disambiguation.

54.4 Physical Features of Keys and Keyboards

This section summarizes experimental and rational investigations of physical aspects of keys and keyboards. Because research has not provided comprehensive data on how the features might interact in affecting typing performance, each aspect receives separate discussion.

54.4.1 Keyboard Height and Slope

Scales and Chapanis (1954) conducted an experiment to determine the best slope for keysets used by long-distance telephone operators. People who had no previous experience with this keyset entered sequences of letters and numbers with the keyset sloped at either 0, 5, 10, 15, 20, 25, 30 or 40 degrees for each session. There were no differences in speed or errors among the eight slope conditions. All participants preferred some slope over a flat (zero degree) keyset; half of them preferred an angle between 15 and 25 degrees.

Galitz (1965) tested a computer keyboard at 9, 21, and 33 degrees. Although there were no performance differences due to keyboard slope, typists preferred the 21-degree angle. This slope was closest to the 16- to 17-degree angle on equipment the typists normally used. Galitz recommended that computer keyboards

[4] It is also possible to apply disambiguation techniques to the design of special-purpose keyboards that do not conform to the layout restrictions of a telephone keyset. For an example, see Kreifeldt, Levine, and Iyengar (1989).

have a slope adjustable between 10 and 35 degrees to satisfy individual preferences.

Emmons and Hirsch (1982) compared three slopes for an IBM 30 mm keyboard. Because a change in angle also resulted in a different home-row height, their height (angle) settings were 30 mm (5 degrees), 38 mm (12 degrees), and 45 mm (18 degrees). They also used a non-IBM 30 mm (5 degrees) keyboard. Tests of 12 experienced typists revealed no differences in error rates among the three angles/heights. With regard to typing speed, the 38-mm and 45-mm keyboards resulted in faster rates than either of the 30-mm keyboards. Typists preferred the 45-mm keyboard most and the 38-mm keyboard second-most. When asked about discomfort, five participants found everything uncomfortable, five said the 30-mm keyboard caused discomfort, one reported the 45-mm keyboard as uncomfortable, and one person had no discomfort with any of the keyboards.

Miller and Suther (1981; 1983) examined preferences for keyboard slope and height. U.S. and Japanese participants from the 5th, 50th, and 95th percentiles in height (compared to their respective populations) adjusted a workstation to their preferred settings and then transcribed some text from a written document into a computer terminal. Keyboard slope settings ranged from 14 to 25 degrees with an average of 18 degrees. Preferred slope significantly correlated with seat height (r=.71) and with individual stature (r=.43). Short people or people who preferred lower seat heights also liked to have a keyboard with a steeper slope. Because stature correlates with hand length, a steeper slope makes it easier for short-handed people to reach all of the keys. They recommended that keyboard slope be adjustable up to at least 20 degrees (with 25 degrees being better) to suit individual preferences. The keyboard used in the study was 77 mm high. Preferred home-row height was 637 to 802 mm above the floor, with an average of 707 mm. Keyboard height significantly correlated with stature (r=.71), preferred seat height (r=.74), and preferred CRT height (r=.57). They recommended that keyboards be as thin as possible to satisfy table-height requirements and that users be able to independently raise and lower the keyboard-support surface relative to the display.

In Suther and McTyre (1982), experienced typists used a thin-profile (30 mm) keyboard at 5, 10, and 25 degrees and a thick-profile keyboard at 15 degrees. There were no differences in typing performance for the four angles. None of the typists preferred the 5-degree keyboard. One person liked 25 degrees best, and the rest of the typists rated the 10- and 15-degree keyboards as preferable. This study also found preferences related to stature and hand length. Taller people and those with long hands tended to like the lower slope, but short people and those with short hands liked the steeper slope. Suther and McTyre recommended that keyboards have an adjustable slope between 10 and 25 degrees.

Abernethy (1984) and Abernethy and Akagi (1984) compared a 30-mm (8 degrees) keyboard with a 66-mm (12 degrees) keyboard. They reported that typists' hands tended to "curl" more with the 30-mm keyboard. That is, "the fingers curved around more as though they were forming a [loose] fist . . . for the lower keyboard" (C. N. Abernethy, personal communication, September 12, 1985).

A comparison of the same 30-mm keyboard with a 44.5-mm (8 degrees) keyboard showed that the wrist angle "pronated" more with the lower keyboard. Pronation describes the motion of the hand turning inward about the axis of the wrist, such that "the wrist angle flattened out, becoming more parallel to the floor, from the higher to the lower keyboard height" (C. N. Abernethy, personal communication, September 12, 1985). Pronation was greater when the keyboards were on a lower typing stand than when they were at desk height (8 degrees pronation compared to 5 degrees pronation). In another test, a modified 30-mm keyboard allowed adjustment of the slope from 8 to over 30 degrees. The average angle chosen by participants was 16.1 degrees at desk height and 14.4 degrees at typing stand height.

Najjar, Stanton, and Bowen (1988) examined typing performance and preference for standing typists using three keyboard home row heights (74, 99, and 125 cm) and three keyboard angles (O-, negative 15- and positive 15- degree slopes). At the lowest home row height, performance with 0- and negative 15-degree slopes was significantly better than with the positive 15 degree slope. Participants preferred typing on the 0-degree and positively sloped keyboards at the medium and highest home row. Using a positively sloped keyboard at the lowest home row height appeared to result in significant wrist dorsiflection (hands bent upward at the wrist), producing discomfort for the standing operators.

In an experiment designed to simulate dual-task conditions in aircraft cockpits, Hansen (1983) tested three slopes for a small keypad. There were no performance differences between 0-, 15- and 35-degree slopes, but 75 percent of the pilots tested preferred the 15-degree slope.

Burke, Muto, and Gutmann (1984) tested a keyboard with a fixed 11-degree slope at four heights (35,

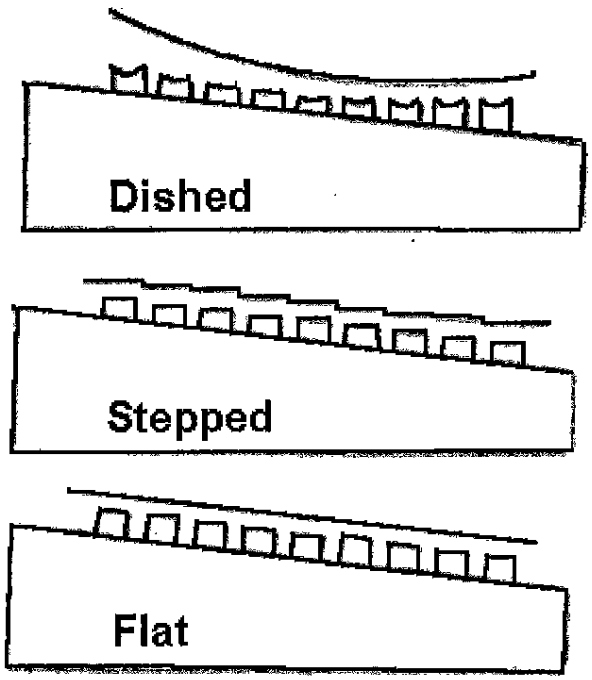

Figure 1. Keyboard profiles.

64, 84, and 104 mm). Again, there were no significant differences in either speed or accuracy of performance. The participants expressed the least preference for the height of 35 mm and the greatest preference for the height of 84 mm. The 64-mm keyboard also received high ratings.

Conclusions

The results of this research show that a wide range of keyboard heights and slopes do not appear to affect typing performance. Typists appear to prefer some slope in a keyboard. The angle of slope should be adjustable to at least 15 degrees, and perhaps even steeper to accommodate individual preferences. These conclusions are consistent with the ANSI/HFS 100-1988 standard's recommendation to provide a keyboard slope between 0 and 25 degrees (preferably limited to the range of 0 to 15 degrees) (Human Factors Society, 1988).

The height and slope of keyboards became a matter of debate when the West Germans announced their requirement for low-profile (30 mm) keyboards having a slope of no more than 15 degrees, enforcing this since January 1, 1985. Long-term comfort and avoidance of muscular strain appear to be the primary considerations behind the law. Although the 30-mm requirement caused quite a stir when first proposed, keyboard designers, manufacturers, researchers and users have come to accept low-profile keyboards (Paci and Gabbrielli, 1984).

54.4.2 Detachable Keyboards

There is no research available on the need for keyboards that are detachable from the display housing. The purpose of detachable keyboards is to satisfy individual sizes, preferences and task needs for locating the keyboard on the work surface.

The advantage of a detachable keyboard might be limited by the selection of work surfaces. Although a separate keyboard-support surface increases flexibility for height of the keyboard, it can reduce flexibility for placing the keyboard to one side of the workstation. Locating the keyboard support at the center of a workstation might interfere with tasks that do not require the use of a keyboard.

Another important point is that it is not always necessary to have a detachable keyboard. For office tasks that are brief or infrequent, users might not need a detachable keyboard. Laptop computers might be more difficult to use if the keyboards were separate. For public access terminals, a detachable keyboard might even be a liability.

Keyboard Profile

The relative angles and placement for different rows of keys on the keyboard create the keyboard profile. Most keyboard profiles conform to either a flat (on which keytops are parallel to keyboard slope), dished, or stepped design (see Figure 1).

Only two studies to date have tested different keyboard profiles. Paci and Gabbrielli (1984) evaluated performance by three typists using either a stepped or a dished profile keyboard. The angle at which the typists' fingers touched the keys ranged from 2 to 13 degrees on the stepped keyboard and from 8 to 11 degrees on the dished keyboard. Performance was reportedly better with the dished profile, and the typists expressed a preference for this keyboard. However, these effects might be the result of a difference in slopes because the stepped keyboard had a 9-degree slope and the dished keyboard had a 12- degree slope. Paci and Gabbrielli recommended the dished profile for the alphanumeric keys, the stepped profile for the numeric keypad (because this is common for calculators), and a flat profile for function keys because visual requirements (such as labeling and readability) are more important for these keys.

Magyar (1985) compared performance and preference of twelve typists using a flat, a dished, or a stepped keyboard profile. Each operator performed twenty timed typing trials per day with each of the three keyboard profiles. The typists received feedback on throughput and error rates after each trial, and completed a questionnaire daily after using each keyboard. Throughput performance with the flat keyboard was significantly lower than that for either the dished or stepped keyboards, which were not significantly different. Although detected error rates were comparable across all three profiles, undetected errors with the flat keyboard were significantly higher. Deficits inherent in the configuration of the keyboard used for the test prevented the detection of a clear-cut preference for any particular keyboard profile. Typists complained that the size and placement of the backspace, enter, and shift keys made typing difficult independent of the differences in the specific keyboard profile. Nevertheless, it appeared that the stepped and dished keyboard profiles were superior to the flat profile.

Conclusions

Although there might be subtle performance differences between flat, stepped, and dished keyboards, recommendations generally agree that the stepped and dished profiles are acceptable. There is insufficient data, however, to warrant a firm conclusion regarding the purported superiority of the dished and stepped designs over the flat profile. The data suggest that the influence of keyboard profile on user performance and preference might be minimal relative to the influence of other keyboard parameters.

54.4.3 Key Size and Shape

With the proliferation of portable devices, keyboard designers have a great desire to reduce the size of their keyboards by reducing the size of keys, but need to understand the impact of reduced key size on typing performance. Because the keytops are the point of immediate contact between a user and a keyboard, the size and shape of the key might have a lot to do with typing performance. However, relatively little research has addressed this hypothesis (with less for shape than size). Alden et al. (1972) stated that the design of individual keys depended more on "design convention rather than empirical data" (p. 280).

Clare's Proposals

Clare (1976) proposed four goals for the design of key shapes:

1. The operator should be able to see the key label.
2. The finger should be able to locate the key without hitting other keys or fingers.
3. The distribution of pressure on the finger should indicate the location of the finger on the key.
4. The force of pressing the key should be distributed to the proper portion of the finger.

Clare recommended that key tops should be 12.7 mm square and have a distance of 19 mm between keytop centers. Smaller keytops (such 9.5 mm) were "less satisfactory" (p. 102).

Calculator Key Size

Deininger (1960) tested different key sizes and shapes for a ten-key numeric keypad. Keying times and accuracy improved when key size increased from 9.5 to 12.7 mm. To provide guidance for the development of numeric keypads for portable computers, Loricchio and Lewis (1991) had 15 participants use three commercial calculators with different key spacing and key size. There were no significant accuracy differences, but user preference and speed improved as the key size increased from 10 mm square to a key measuring 14 x 10 mm.

Alphanumeric Keyboards

PC Magazine (Rosch, 1984) reported the results of a typing test to evaluate various computer keyboards. Typing performance was much poorer with keyboards having small keys. When typists used these same key mechanisms with larger keys, performance was among the best for the eleven keyboards tested. Loricchio and Kennedy (1987) investigated the effect of reducing vertical key spacing from 19 to 15 mm. They found no difference in keying rates or errors after 2.5 hours practice, but there was a strong user preference for the standard 19 mm key spacing. Wiklund, Dumas, and Hoffman (1987) conducted a walk-up-and-use (no practice) evaluation of four commercially available keyboards for both two- and one-handed use. Key spacing ranged from 19 x 19 mm to 13 x 12 mm. Although Wiklund et al. conducted no statistical analyses, the reported mean typing rate was greater for the largest keys, regardless of whether participants used one or two hands. For all keys except the smallest, two-handed typing was faster than one-handed typing.

Some guidelines cite round keys as acceptable, but square keys might be better because they provide more surface area within the same amount of space between keytop centers (Cakir, Hart, and Stewart, 1980). In an evaluation that included keycap differences, typists

preferred keycaps that "resemble the somewhat rounded, dished keycaps of earlier model Selectric typewriters" (Texas Instruments, 1983, p. 26). The next most preferred keys were those with large, square touch surfaces with a cylindrical indentation from front to back. The keyboard with round keytops received the worst ranking.

Conclusions

The center-to-center spacing of keys on standard alphanumeric keyboards is generally 19 mm. Use of smaller center-to-center spacing will result in slower typing. There are no data available on upper limits for key size, but there is little incentive to explore the upper limit. Designers usually seek to minimize rather than maximize the size of their keyboards (especially in the development of portable devices). Clearly, designers should strive to provide full-size (19 mm spacing) keys for the major typing areas of their keyboards (certainly the alphanumeric area and, if possible, the numeric keypad). This conclusion is consistent with the recommendation provided in ANSI/HFS 100-1988 (Human Factors Society, 1988) that horizontal spacing should be between 18 and 19 mm and vertical spacing should be between 18 and 21 mm. The ANSI-HFS 100-1988 recommendation for the minimum striking surface width is 12 mm.

With regard to the shape of keys, there is some evidence that they should fit the shape of the finger tip for ease of location and finger placement. Preferences appear to lean toward keys that have spherical indentation as opposed to those having a cylindrical indentation. The ANSI/HFS 100-1988 standard (Human Factors Society, 1988) makes no recommendation regarding indentation, and states that any keytop shape (square, round, or rectangular) is acceptable as long as the keys conform to the recommended key spacing.

54.4.4 Key Force, Travel and Tactile Feedback

The "force/displacement" function of a key describes the force with which a finger must press the key to actuate it and the distance the key travels before, during and after actuation. A generalized force/ displacement function appears in Figure 2, which shows:

- on the horizontal axis, the distance the key travels
- on the vertical axis, the force applied to the key
- separate curves for the downstroke and upstroke of the key (arrows show the direction of travel)
- the key's actuation point ("switch closed")

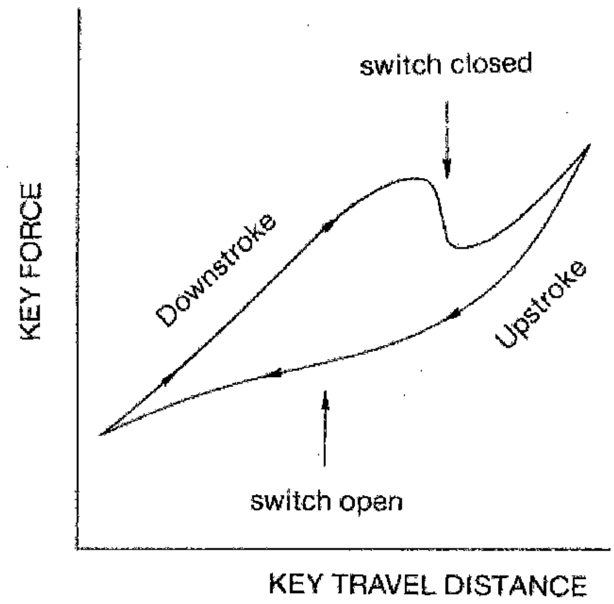

Figure 2. A generalized force-travel function.

- the "switch open" point at which pressing the key creates another character
- changes in the slope of the function corresponding to the "feel" of the key at different points along its travel
- tactile feedback caused by a rapid drop in force before the "switch closed" point and a subsequent increase in force beyond this point
- hysteresis, that the "switch open" and "switch closed" points occur at different places along the key's travel

Studies on the effects of different force/ displacement functions have not been systematic, so it is difficult to create a model of how a particular aspect of the function will affect keying performance or preference. Research has uncovered ranges within which neither the amount of key force nor the distance of travel affects performance. Other investigations have compared keyboards for which the entire force/travel function varied.

Studies on Key Force and Displacement

A study of telephone usage and occasional data entry (Deininger, 1960) found no performance differences due to either a decrease in maximum force from 14.1 to 3.5 ounces (400 to 100 grams) or a decrease in maximum travel from 0.19 to 0.03 inches (4.8 to 0.8 mm).

Kinkead and Gonzalez (1969) found key pressing performance was best at low levels of force and travel. They recommended values between 5.3 and 0.9 ounces (150.3 and 25.5 grams) for force and between 0.25 and 0.05 inches (6.4 and 1.3 mm) for key travel.

In a similar study, Loricchio (1992) compared text entry typing on keyboards having identical key travel (2.7 mm) but different operating-point key forces (58 grams vs. 74 grams). Although there was no difference in error rates between the two keyboards, throughput speed was significantly faster on the 58 gram keyboard. Test participants also highly preferred the lighter force keyboard over the heavier touch keyboard. Because Loricchio compared only two forces, however, the data in this study did not indicate if further decrements in force would continue to improve or degrade performance (but see Akagi, 1992, below).

Switch Technology or Key Force?

Brunner and Richardson (1984) compared three switch technologies: a snap-spring keyboard that had a very slight drop-off in force before the point of actuation and a gradual increase in force after this point; a linear-spring keyboard that had no change in the force/displacement function to indicate tactile feedback; and an elastomer switch that provided distinct tactile feedback. Considering both speed and errors, the elastomer keyboard was about 2% to 6% better than the other keyboards. Incorrect insertions of characters occurred more often on the linear-spring keyboard. Ratings by typists indicated that the elastomer keyboard was acceptable relative to the other keyboards tested. It is not possible, however, to determine exactly which keyboard features caused the performance differences reported in this study.

A factor that might have influenced the results of this study was the different key force for each type of keyboard. A snap-spring keyboard key force is typically about 70 grams, an elastomer-dome keyboard key force is about 60 grams, and a linear-spring key force is about 30 grams (Akagi, 1992). Using this reasoning, Akagi compared preference and performance of four keyboards having different key forces and travel characteristics. He had participants type with two linear-spring keyboards, one with low force (42.5 grams) and one with high force (70.9 grams), and with two snap (tactile) action keyboards, one with low force (35.5 grams), and one with high force (70.9 grams). While a majority of the test participants typed faster on the linear-spring keyboards, typing speed was not significantly different between the tactile and linear-spring action keyboards. Error rates, however, were significantly higher on the low force keyboards than on high force keyboards for both the tactile and linear-spring action keyboards. The typists distributed their preferences evenly among the four keyboards tested. Akagi suggested that an optimally designed keyboard should be a tactile-spring keyboard having a key force midway between the values he used in his test (approximately 57 grams). This recommendation is consistent with the results provided by Loricchio (1992, see above), who reported that a tactile action keyboard having a key force of 58 grams produced superior performance over a similar keyboard with heavier key force (74 grams).

Key Movement

In another study, typists rated smooth key movement as a highly important facet of keyboard quality (Monty, Snyder, and Birdwell, 1983; Texas Instruments, 1983). Comparing six keyboards, the factors that seemed to be most important to users were:

1. key switches that do not have noisy key bottoming
2. tactile-snap feedback caused by an abrupt change in the force required to actuate the key
3. a force/displacement curve shaped like a "roller coaster"
4. a smooth force/displacement curve undisturbed by jitter
5. keycaps with minimal lateral wobble

Because the performance data showed a speed-accuracy tradeoff, it was impossible to determine the specific effects of different force/travel curves on performance.

Experiments with Capacitance and Membrane Technologies

Touch keys that lack key travel (such as capacitance and membrane technologies) appear to cause slower keying performance than conventional mechanical keys (Cohen, 1982; Pollard and Cooper, 1979). Although the disadvantage of these switches decreases as users adapt to the absence of tactile feedback, the addition of cues such as embossed edges, metal domes, and tones or clicks on actuation can reduce the early negative effects (Roe, Muto, and Blake, 1984).

Barrett and Krueger (1994) compared performance and acceptance by touch typists or casual users using either a tactile keyboard having full travel and kinesthetic feedback or a flat piezo-electric keyboard with-

out any tactile or kinesthetic feedback. Throughput performance and accuracy by both subject groups were significantly higher on the conventional keyboard, and the flat keyboard had a more adverse effect on touch typists' than casual users' performance. In contrast to previous reports, however, performance on the flat keyboard did not improve with practice, and the authors concluded that touch typists were unable to adapt to the absence of tactile feedback. Analysis of the subjects' video data suggested that the reason for the subjects' failure to adapt was that the removal of kinesthetic feedback effectively reduced their level of skill (from touch typist to casual user) by increasing their dependence on visual feedback from the flat keyboard. Adding peripheral cues to a non-tactile keyboard (via audio feedback, embossed edges on keys, etc.) should consequently enhance performance by reducing the need for typists to look at the keyboard. Indeed, there is mounting evidence that auditory feedback in part may influence or interact with the degree of tactile feedback reported by typists (Brunner and Richardson, 1984; Magyar, 1986d; Pollard and Cooper, 1979; Roe, Muto, and Blake, 1984).

Key Force and Finger Force

Clare (1984) recommended that force/ displacement curves should differ for different fingers and key locations. According to Clare, upper keys should have shorter travel and lower keys should have longer travel to produce the same feel for the fingers.

Actual measurement of the finger force that typists exert on the keys indicates that the force-displacement characteristics of the keyboard can affect the degree of fingertip forces applied during typing performance. Rempel and Gerson (1991) collected peak fingertip forces for each keystroke using strain gauge load cells while subjects typed on three keyboards that differed in terms of key force and travel characteristics. While the results showed that the average peak fingertip forces applied by subjects were more than three times greater than the force required for key activation, keyboards requiring less activation force and shorter key travel actually resulted in reducing the subjects' peak fingertip force by as much as 18%.

A subsequent study (Armstrong, Foulke, Martin, Gerson, and Rempel, 1994) replicated the previous results, and found that average peak keystroke forces were lowest on keyboards requiring the least amount of activation force. This study also found that peak forces corresponding to each keystroke were 2.5 to 3.9 times the required activation force, indicating that subjects consistently displaced the keys to their mechanical limits. Although it is not clear whether the subjects failed to respond to the key breakaway force or whether the range of motion following the key activation point was of insufficient distance for the finger to stop, the authors concluded that key force exerted by typists is largely related to the design and stiffness of the keys.

Conclusions

The literature on actuation force and travel indicates minimal effect on performance within a wide range of these parameters. Recommended values range from about 1 to 5 ounces (about 28 to 142 grams) of force and about 0.05 to 0.25 inches (about 1.3 to 6.4 mm) of travel. The increased error rates for Akagi's (1992) light touch keyboards combined with Loricchio's (1992) results suggest that about 55 to 60 grams is a good design point for key force, but 35 grams is too light. These data and conclusions are consistent with the ANSI/HFS 100-1988 standard's recommendation to provide a key travel between 1.5 and 6.0 mm (preferred 2.0 to 4.0 mm) and key force[5] between 25 and 153 grams (preferred 50 to 60 grams) (Human Factors Society, 1988), particularly with respect to the preferred key force.

More important than the amount of force and travel is the tactile feedback caused by a gradual increase in force followed by a sharp decrease in force required to actuate the key (the breakaway force) and a subsequent increase in force beyond this point for cushioning. The result is a curve shaped like a roller coaster. From the data available, keyboards should provide tactile feedback because it improves keying performance and typists prefer it. Capacitive and membrane keys that require only a minimal touch and little or no travel are inferior to conventional keys in terms of typing performance. Because a number of factors appear to affect the perception of tactile feedback, and because many factors could have influenced the results of the relevant studies, more research in this area would clearly be useful.

54.4.5 Auditory Feedback

Auditory clicks, beeps and tones for typewriter keyboards are unnecessary for skilled typists in high speed data entry tasks (Alden et al., 1972). The sound gener-

[5] The ANSI/HFS 100-1988 standard expresses key force in Newtons, with an acceptable force between .25 and 1.5 N, and a preferred key force between .5 and .6 N.

ated by the typewriter's print hammer striking the paper platen provides a sufficiently loud and correlated auditory feedback signal following each key press. However, the advent of personal computers eliminated the auditory feedback provided by impact printers and introduced newer keyboard technology (such as elastomer, capacitive, and membrane switches) that allowed designers to create truly silent key action. These keyboards can have auditory feedback as an add-on feature to turn on and off. Some also allow adjustment of the volume of the click. Performance data with such keyboards indicate that typing is significantly faster and more accurate with auditory feedback on than with it off (Monty, Snyder, and Birdwell, 1983; Roe, Muto, and Blake, 1984). Moreover, most typists prefer auditory feedback, but they also want the ability to turn it off depending on its physical characteristics and the environment in which they use the keyboard.

For telephone keypads there is some evidence that adding a single tone allows faster keying than a click or a visual signal (Pollard and Cooper, 1979). When the user cannot see the keys for dialing telephone numbers, speech feedback reduces keying errors (Nakatani and O'Connor, 1980).

The Timing of Auditory Feedback

The amount of time lag between a key press and the auditory feedback from the print hammer or keyboard is an important variable. If the lag is too long, it can interfere with typing performance (Clare, 1976; Texas Instruments, 1983). Long (1976) showed that when the print mechanism of a teletype was delayed or irregular in relation to typing on the keyboard, speed of typing slowed for both unskilled and experienced typists. The effect disappeared with practice, but only for skilled typists.

Magyar (1982) noted a similar disruption in typing performance for an electronic typewriter that substituted an ink-jet printing mechanism for the standard mechanical impact printer and a relatively silent membrane keyboard instead of a mechanical keyboard. As in Long's (1976) study, the irregular and delayed auditory feedback of the ink-jet printhead following keystrokes resulted in decreased typing speed and increased error rates. Modifying the keyboard to generate a distinct acoustic click after each keypress resulted in significant performance improvements. In trials with the clicker turned "On," typing speed immediately increased and the error rate decreased. Turning the clicker "Off" resulted in immediate decrements in typing speed with simultaneous increases in error rate. Magyar speculated that the quality of the auditory feedback appeared to be important. Operators preferred keyboards providing short duration, low frequency (less than 1000 Hz) auditory feedback sounds such as "clicks" and showed less preference for high frequency (greater than 2500 Hz) "beeps" or tones.

The Interaction of Auditory and Tactile Feedback

Although it is generally accepted that tactile feedback is more important for keying speed than is auditory feedback, there is mounting evidence suggesting that the two variables may exert significant interactions influencing both performance and preference (Roe et al., 1984; Magyar, 1986d; Walker, 1989).

Brunner and Richardson (1984) evaluated performance and preference for experienced and occasional typists across several keyboards having different levels of tactile feel and auditory feedback. They reported that auditory feedback was the most important determinant of a user's initial reaction to a keyboard. The importance of auditory feedback, however, diminished over time. Although there was no difference in typing performance across keyboards for either group, the occasional typists rated their performance as better on keyboards having auditory feedback.

Schuck (1994) examined the effect of auditory feedback on the performance of operators typing on a touch-screen keyboard having no key travel. Results revealed that the feedback did not affect error rates, but the addition of auditory feedback to a typing task did improve typing speed under all tested conditions. These results might not generalize to a more skilled typing population. The actual experience level of the typists was not clear because operators rated their own level of typing skill. It seems likely that the typists were not highly skilled because throughput speeds during the test appeared to be rather slow (12-25 wpm).

In a test comparing a buckling-spring keyboard having tactile feel against a much quieter membrane keyboard with little tactile feel, Magyar (1986d) initially reported an even split of the preferences of experienced typists across the two keyboards. The typists who preferred the buckling-spring keyboard cited its superior touch and feel, while those who preferred the membrane keyboard liked its quietness. In a replication of the study (using the same keyboards), typists listened to "white noise" played through headphones to mask differences in auditory feedback between the two keyboards. Results of the second study revealed a shift in preference to the buckling-spring keyboard, with the majority of typists citing superior touch and feel as the

basis for their preference. Magyar concluded that, in the absence of auditory feedback, users appeared to base their preference primarily on the tactile characteristics of the keyboards.

Conclusions

Auditory feedback appears to have a positive effect on typing performance and user preference, especially for keyboards having little or no tactile feedback. While there is some evidence indicating a possible interaction between auditory and tactile feedback, the exact relationship between these two variables is unclear. If designers add auditory feedback to a keyboard, they should also provide operators with a way to control the presence or absence of the sound (preferably with a volume control for maximum user flexibility). Although auditory feedback appears to be an important determinant of keyboard usability, the physical values defining its "optimum" characteristics (such as the ideal amplitude, frequency, and timbre) still require investigation.

54.4.6 Visual Feedback

Common sense suggests that it might be helpful to have a visual display of a telephone number to reduce errors when dialing the phone. However, E. T. Klemmer (personal communication, December 10, 1981) found such a display to be "of no value for ordinary dialing of telephone numbers." Visual displays for telephones appear to offer no advantage because "telephone users can easily operate with an acceptably low error rate without the display and the effort involved in checking the display is not worthwhile. Moreover, if the user suspects that an error was made (more than half of all errors are self-detected) it is more efficient to simply re-key the number than to read the display, check for accuracy, and then re-key the number" (E. T. Klemmer, personal communication, December 10, 1981). (For very long numbers, such as those used when sending faxes internationally, a visual display might be helpful. We know of no research in this area.)

For touch typists on regular keyboards, visual feedback does not appear to provide any advantage for speed of typing, but it does affect the typist's ability to catch and correct errors (Alden et al., 1972; Rosinski, Chiesi, and Debons, 1980). With fewer than 9 characters displayed at a time, typists were less likely to correct their own errors (Rosinski et al., 1980) than with a larger number of letters displayed. Visual feedback also might be useful when first learning to type (Alden et al., 1972).

As with auditory feedback, timing of visual feedback is important. When the print mechanism of a teletype was delayed and irregular in relation to typing on the keyboard, speed of typing slowed for both unskilled and experienced typists (Long, 1976). The effect disappeared with practice, but only for skilled typists. Delay of visual feedback on a computer display also affects typist behavior and satisfaction (Williges and Williges, 1981; 1982). Boyle and Lanzetta (1984) found that the perceptual threshold of delay for subjects typing at a computer was 165 ms for single keystrokes, and 100 ms for multiple keystrokes.

54.4.7 Error-Avoidance Features

Variables such as rollover, buffer length, hysteresis and repeat functions can affect the rate of typing errors, but have not received experimental investigation.

Rollover

Rollover is the ability of the keyboard to store each keystroke in proper sequence. Without rollover, typists must release each key before pressing the next. High-speed typing without rollover results in some character loss or generation of erroneous codes. Two-key rollover will generate two keystrokes accurately when a typist presses the second key before releasing the first. With n-key rollover, any number of keystrokes can overlap without disturbing the proper sequence of characters.

Another aspect of rollover is shadow rolling, which refers to the sequence of keystrokes in which the typist presses and releases the second key before releasing the first. Shadow rolling with two-key rollover does not generate the second character. With n-key rollover, the sequence will be correct. Thus, n-key rollover is better than two-key rollover (Cakir, Hart, and Stewart, 1980; Davis, 1973).

Hysteresis

Actuation occurs at the "switch closed" point on the downstroke (see Figure 2). Upon release, the switch remains closed until the key travels past the "switch open" point. If the closed and open points occur at the same place, it is possible to experience extra, unwanted keystrokes when the typing finger hesitates or is not smooth on the upstroke (key bounce). Hysteresis (the travel distance between the "switch close" and "switch open" points) eliminates this problem. With hysteresis, the switch remains closed on the upstroke past the actuation point on the downstroke.

Interlocks

If the key does not have mechanical hysteresis, an electronic interlock can provide the same benefit. On most modern keyboards, an electronic polling scheme imposes a minimum time between keystrokes. The system assumes short inter-key times are due to key bounce or unintended keystrokes. The effect of the interlock is to transmit keystrokes at a controlled rate, ignoring these short inter-key times.

The optimal transmission rate depends on maximum keying rates, which usually occur in fast bursts of typing. If the interlock period is too short, it will not be effective at screening out unintended keystrokes. Recommendations for interlock systems vary, but in general should account for a typing rate of at least 100 gross words per minute. This value represents an interlock period of about 100 msec. Because typing burst rates can be much faster than 100 msec per keystroke (as low as 4 msec for skilled typing of certain digrams), shorter interlock intervals might be necessary. Alden et al. (1972) proposed a lower limit of 50 msec. A firmer recommendation will require further research.

Buffer Size

Many computer keyboards allow the user to type ahead of the display. This feature is particularly useful when the display depends on the response of the system. If the user knows ahead of time what input to enter next, he or she can store keystrokes in a buffer until the system is ready to receive them.

In a comparison of buffers storing 1, 2, 4, 6 and 7 characters, buffer size interacted with the speed of visual feedback in determining typing speed (Williges and Williges, 1981; 1982). With a fast visual display, smaller buffers did not affect typing speed. A display delay of as much as 1.5 seconds required a larger buffer. Buffer size was less important than speed of visual display: long delays in visual feedback resulted in slower performance regardless of the size of the buffer. Because computer response times often result in delayed visual feedback, the recommended buffer size is at least seven characters.

Repeat Features

Although there are no experimental data to support the need for key-repeat features, experience shows that "typamatic" keys are handy for many purposes, such as underlining and other graphic symbols used to make tables. On many computer keyboards, all keys are typamatic. The delay before creating repeated characters after pressing and holding the key should be neither too long nor too short, but the literature does not contain any specific recommendations for the optimal delay length. A common default value for the delay is 0.5 seconds between the first and second productions of the key on a single press, and with 0.1 seconds between subsequent key productions.

54.4.8 Color and Labeling

Recommendations for the color and labeling of keys and keyboards typically rely on the requirement for visibility and for coding purposes, rather than experimental investigations. Neither the keys themselves, nor the entire keyboard should be so shiny as to create a glare source. The usual recommendation is a matte to silky matte finish. The names of keys should be legible and understandable to the user. A slightly rough (matte) finish on the keytops aids finger positioning but should not reduce the legibility of the key label. Grouping and coloring keys by function assist visual search. This is particularly helpful on computer keyboards, because they usually act as more than typing devices for text entry (Cakir, Hart, and Stewart, 1980).

Lewis (1984) conducted a study on different designs of an Alternate key to determine if, because the primary purpose of an Alternate key is to place other keys into an alternate state, the color and position of the word "Alternate" on the Alternate key should look like a primary function or, for ease of association, if the word "Alternate" should look like an alternate function. The three variables examined were position (the word "Alternate" appeared at the position of the primary or the alternate function for the non-alternate keys), color (the word "Alternate" was either the color of the primary or the alternate functions), and background (the Alternate key's background either matched or failed to match the color of the alternate functions). He found that the subjects made the fewest selection errors (primary versus alternate functions) when the color and position of the word "Alternate" matched that of the alternate functions on the other keys.

54.4.9 Special Purpose Keys

The special purpose keys are the keys that are not part of the standard alphanumeric typing area or the numeric keypad, such as the Backspace key, the Enter key, the cursor control keys, and the function keys. Some relatively recent research has addressed the design of these keys.

The Enter and Backspace Keys

The Enter key has assumed a variety of shapes on modern keyboards, including the vertical Enter key (taller than wide), the horizontal Enter key (wider than tall), and the backwards-L shaped "dogleg" Enter key, which occupies the combined space of the vertical and horizontal Enter keys. In a series of studies, Magyar (1984; 1986b; Magyar and Robertson, 1986) determined the order of typists' preference and performance with the three types of Enter keys is dogleg first, horizontal second, and vertical third. Typists weakly preferred the dogleg Enter to the horizontal Enter, and significantly preferred both the dogleg and horizontal Enter keys to the vertical Enter key. The speed of acquiring all three types of Enter keys appeared to be equal, but the magnitude of acquisition errors for the vertical Enter key was roughly twice that of the dogleg and horizontal Enter keys.

Backspace keys typically occupy either the space of one (single-wide Backspace) or two (double-wide Backspace) normal keys, and are usually located in the upper right corner of the standard typing area. Magyar (1984, 1986b) conducted studies to evaluate user preference for and performance with the two types of Backspace keys, and found that people prefer and perform better with the double-wide Backspace. The error rates for the horizontal and dogleg Enter keys were about equal, but the ratio of errors for the single-wide relative to the double-wide Backspace key was 24.0 for simple text (typing restricted to the QWERTY area) and 9.0 for complex text (input text included non-alphanumeric characters).

Kennedy and Lewis (1985) conducted a small field study to determine the relative rates of acquisition of the Backspace and Enter keys when people used both word processing and spreadsheet programs. The results showed that the ratio of Enters to Backspaces was 2.2 for word processing and 5.3 for spreadsheets.

Considerations of these findings suggest that the best keyboard design (disregarding keyboard real estate limitations) would include both the dogleg Enter key and the double-wide Backspace key. If keyboard real estate limitations lead to a tradeoff in the space allocated to the Enter and Backspace keys, the best tradeoff would result in a horizontal Enter key and a double-wide backspace key. Although typists typically acquire the Enter key more often than the Backspace key (Kennedy and Lewis, 1985), the increase in typing errors due to reducing the size of the Backspace key is enough greater than the increase in errors due to reducing the Enter key to a horizontal shape to justify a keyboard design with a double-wide Backspace key and a horizontal Enter key.

Cursor Control Key Arrangements

The cursor control keys are the arrow keys used to move the cursor (the on-screen symbol that indicates the focus of typing -- where any typed input will appear on the screen). A number of different layouts for these four keys have appeared in various keyboard designs. The most common arrangements are the box, cross, and inverted-T. The box arrangement has the left and right arrow keys located directly under the up and down arrow keys in a 2 by 2 key matrix. Thus, the box arrangement has appropriate control-response compatibility for left and right, but not for up and down. The cross arrangement has the arrow keys arranged around an empty key space, with the left and right arrow keys on the left and right of the empty space, and the up and down keys located above and below the empty space. This arrangement creates correct control-response compatibility for all four keys, but is somewhat awkward to use. The inverted-T arrangement is similar to the cross, but the down arrow key occupies the empty space of the cross arrangement. This results in an inverted-T shape, with the left and right arrows located to the left and right of the down arrow, and the up arrow immediately above the down arrow.

Emmons (1984) demonstrated the superiority of the cross layout over the box layout, especially for inexperienced users. In a following study, Emmons (1987) found no performance difference between the cross and inverted-T arrangements, but reported that 13 of 18 participants preferred the inverted-T. Magyar (1986c) reported similar results.

Function Keys

Function keys are keys that operate as defined by software. There is no published research on different function key arrangement. Although this seemed to be a promising area of research when this chapter first appeared (Potosnak, 1990), recent developments in graphical user interfaces (specifically, the use of mice and on-screen buttons) have reduced the importance of such research, making future research in this area unlikely.

54.5 Alternative Keyboard Designs

A number of investigators have studied physical reconstruction of the keyboard and modifications in the means of operating a keyboard. The two major areas of

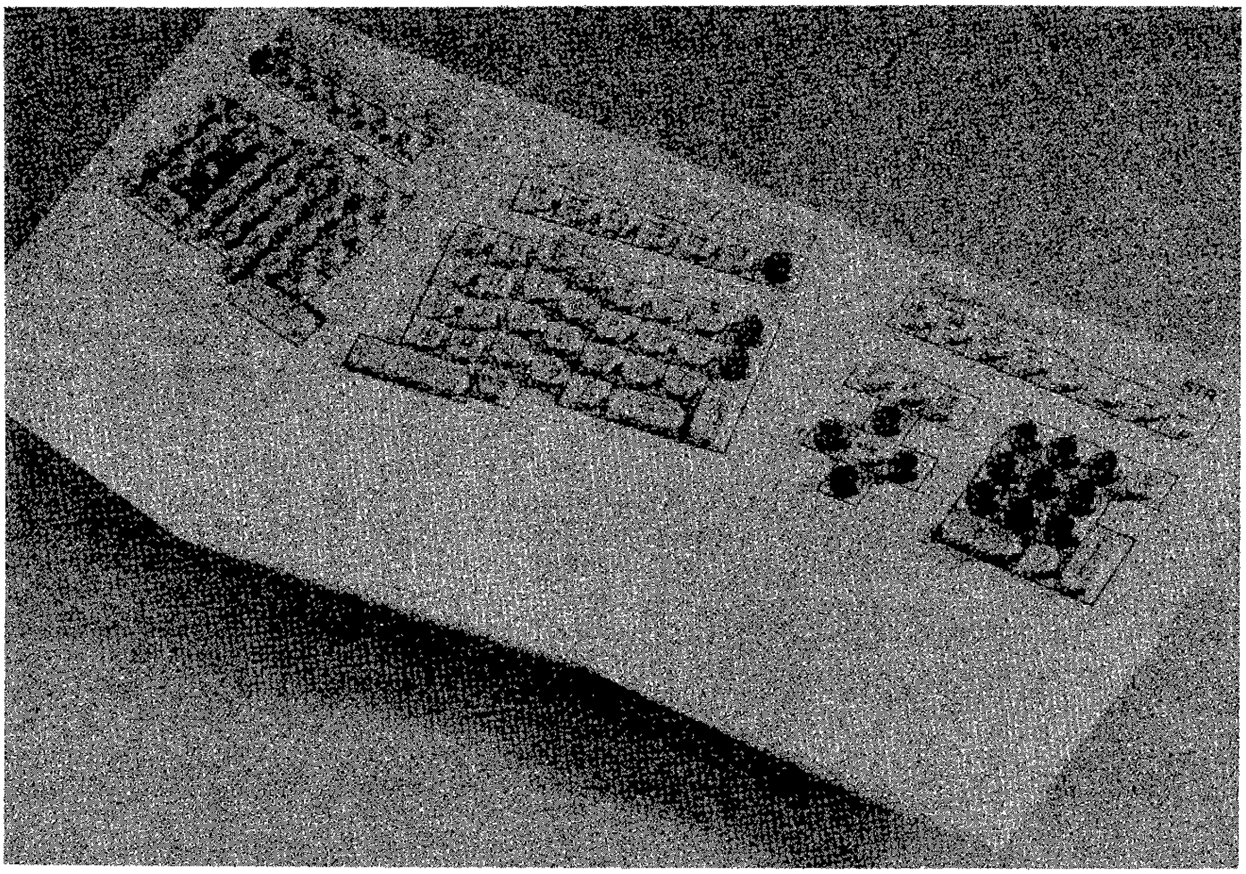

Figure 3. The STR split keyboard of Nakeseko et al.

research in such alternative keyboards are split keyboards and chord keyboards.

54.5.1 Split Keyboards

Studies of how people naturally hold their hands and arms compared to their postures at conventional typewriters have led some researchers to hypothesize that there might be components of fatigue inherent in the design of conventional keyboards (Kroemer, 1972; Nakaseko, Grandjean, Hunting, and Gierer, 1985; Zipp, Haider, Halpern, and Rohmert, 1983). Consistent with these observations, several ergonomists and inventors have developed or contributed to the development of "ergonomic" split keyboards. These keyboards have at least two sections, angled apart in the horizontal plane (producing non-parallel key rows). Some also angle the keyboard sections down from the horizontal plane. Some split keyboards have fixed angles, while others allow a range of adjustment. See Figure 3 for an example of a split keyboard.

The split keyboard literature is too large to review comprehensively in this chapter, but see Lewis (1994; 1995a) for recent literature reviews and Lewis (1995b) for a meta-analysis of preference for split keyboards. This section contains a review of the research conducted with two older split keyboards (the K-keyboard and the STR™ keyboard) and two newer split keyboards (the Kinesis™ keyboard and the Health Comfort Keyboard™).

The K-Keyboard

Kroemer (1972) named his K-keyboard for Klockenberg, an early proponent of split keyboards who published a critique of the standard typewriter in 1926. The K-Keyboard's 30 keys were in straight columns, with curved rows to attempt to fit different finger lengths. The space bars (one for each hand) curved to fit the reach of the thumb, and the keyboard provided a generous area for palm supports. Because the keyboard was experimental, Kroemer did not completely deter-

mine the assignment of characters to keys, but assigned characters to 16 of the 30 keys so the participants in his experiments could type the same sentence repeatedly.

Experiments with the K-keyboard indicated that the degree of lateral tilt of the two halves did not affect key tapping frequency or errors (Kroemer, 1972). Of the angles tested (0, 30, 60 and 90 degrees from horizontal), the data presented suggested that typists preferred an angle of 60 degrees over no tilt. (These data, however, are difficult to interpret due to discrepancies between the description of the assignment of participants to conditions and subtotals for the associated table of results.) In another test, typists made significantly more errors (about 5% more) on a standard keyboard than on the K-keyboard with a 45-degree tilt. Kroemer (1965) attributed this difference in errors to differences between the keyboards' key arrangements rather than to effects of keyboard geometry. In particular, the standard keyboard contained extra keys (relative to the K-keyboard) in its top two rows that seemed to be responsible for a number of the errors made with the standard keyboard. There were no differences either in typing speed or the number of heart beats (used as a measure of circulatory strain). Kroemer reported that participants terminated the task for different reasons. Users of the standard keyboard more often complained of "aches and pains," while K-keyboard typists were more likely to report that they could not concentrate any longer (although this group also reported some aches and pains). Kroemer did not treat these results with any statistical test. A clear comparison of the two keyboard geometries was not possible in these experiments because the K-keyboard had built-in palm supports, but the standard keyboard did not.

The STR Keyboard

Nakaseko and his colleagues (Nakaseko, Grandjean, Hunting, and Gierer, 1985) conducted experiments to test different opening angles between halves, the angle of tilt, and the size of the forearm-wrist support surface of an experimental split keyboard. Later work with this keyboard led to the development of a final product by Standard Telephon and Radio (STR) AG (Buesen, 1984), which won a design award at Ergodesign in 1984.

In an initial experiment, Nakaseko et al. (1985) reported that typists found the split keyboard acceptable and favored the design with lateral tilt of 10 degrees and an opening angle of 25 degrees. In a second experiment, 31 participants typed for 30 minutes with each of three keyboards. One keyboard was a traditional keyboard with a large forearm-wrist support, one was an experimental split keyboard (using the design favored by typists in the preceding experiment) with a large forearm-wrist support, and one was the same experimental split keyboard with a small forearm-wrist support. Participants used the keyboards in randomized orders, and after use completed a questionnaire to indicate if they felt pain in different parts of their upper limbs and shoulders. The experimenters recorded the amount of pressure the participants placed against the forearm-wrist supports and made a number of body posture measurements. They reported their feelings after each trial, using a seven-point scale with the end points of *very relaxed* and *very tense*, and ranked the keyboards according to their preference.

There were no statistically significant differences among the keyboards for reported pains in the neck-shoulder and arm-hand areas. For the relaxed-tense ratings, the keyboards did differ for the arms and hands and the back, with the experimental keyboard with the large forearm-wrist support having the most favorable ratings. None of the average ratings, however, exceeded the center point of the seven-point scale (Neither-Nor). On the basis of the preference ranks, the authors stated, "The traditional keyboard was preferred by a scarce 30%, whereas more than two thirds prefer one of the two experimental keyboards" (p. 185). The authors did not perform an overall statistical test on the preference ranks, nor did they report any performance data.

Examination of the row totals shows that the preference ranks reported in Nakaseko et al. (1985) must be incorrect (Lewis, 1994). With 31 participants, each rank row total should be 31. However, the row total for the ranks of 1 is 32, and that for the ranks of 2 is 30. Therefore, there are one too many first-place ranks and one too few second-place ranks, and no way to tell which column is incorrect. After adjusting the columns in all three possible ways (by subtracting 1 from a first-place rank total and adding it to the corresponding second-place rank total), Friedman tests on all three versions showed that, overall, the preference ranks among the keyboards were not significantly different (p ranged from .3 to .4). Accepting the data as given, a binomial test comparing the first-place ranks for the split (16 first-place ranks) and standard (9 first-place ranks) keyboards with large forearm-wrist supports was not significant (two-tailed p=.22).

In addition to these analytical problems, the experimental design for this study has a fundamental flaw. The authors manipulated two independent variables, each of which had two levels (experimental versus traditional keyboard, small versus large forearm-wrist support). Therefore, the complete design for this

experiment would have had four rather than three conditions. From an experimental design perspective, the condition with a traditional keyboard and a small forearm-wrist support is missing. Nakaseko et al. (1985) chose to emphasize the experimental keyboard when they claimed that two-thirds of their participants preferred the experimental keyboard. However, because the experimental design is a fractional (rather than a complete) factorial, an alternative interpretation is that the data show that more than three-quarters of the participants preferred a large forearm-wrist support to a smaller one. Given this experimental design, it is impossible to separate the effects of keyboard type and forearm-wrist support size.

Brigham and Clark (1986) conducted an experiment to compare the STR keyboard to a standard keyboard. Twenty experienced typists practiced with the keyboards for 20 minutes, then typed for seven 20-minute sessions separated by 5-minute rest periods. Brigham and Clark reported that performance on the standard keyboard was superior to that on the STR for all sessions. Their participants also indicated that they found the standard keyboard more comfortable to use and preferred it.

The Kinesis Keyboard

The Kinesis keyboard is a sculptured, nonadjustable split keyboard, featuring a large forearm-wrist support that extends 14 cm from the home row to the edge. Jahns, Litewka, Lunde, Farrand, and Hargreaves (1991) reported a pilot experiment in which eight healthy typists used the Kinesis keyboard for about eight hours over three experimental sessions. Six of eight participants stated that they preferred the Kinesis overall. This finding, however, was not statistically significant (binomial test two-tailed p=.28) (Lewis, 1994). With about eight hours experience with the Kinesis keyboard, the participants still typed, on the average, slower (about 95% of their baseline speed) and with more errors than on the standard keyboard.

Smith and Cronin (1993) reported an experiment in which 25 participants used both a standard and a Kinesis keyboard to type normal and random text. Unlike the Kinesis, the standard keyboard did not have a built-in forearm-wrist support. All participants practiced with the Kinesis for seven hours the day before using it in the experiment. During the comparative part of the study, half the participants used the standard keyboard first and half used the Kinesis first. The researchers also collected electromyographic (EMG) measurements from 11 of the participants. The EMG results showed significantly lower muscle load for the hand and wrist, but not for the arm or shoulder muscles. Participants typed significantly faster with the standard keyboard, but there were no significant differences in errors. Participants stated they preferred the Kinesis keyboard for comfort, but preferred the standard keyboard for performance.

As part of her dissertation, Lopez (1993) had 36 female touch typists use four keyboard designs over a two-day period: a standard keyboard, a standard keyboard with a contoured wrist rest, the Kinesis keyboard and the Health Comfort Keyboard (HCK™). Twenty of the typists had carpal tunnel syndrome (CTS), and the remaining 16 typists made up a normal control group. On the first day, the participants became familiar with the HCK and Kinesis keyboards, performed two three-minute typing tests with the standard keyboard to establish a performance baseline, then practiced with the Comfort and Kinesis keyboards for 50 minutes each (with order of presentation randomized). Typists took three-minute typing tests at the 30-, 40-, and 50-minute points within each practice session. On the second day, the participants performed typing tasks with the four keyboards. After each typing session, Lopez made various physiologic measurements and participants completed various questionnaires, including ranking the keyboards from least to most preferred. Most of the physiologic measurements (nerve conduction velocity, vibrometry, hand strength, hand and distal forearm volume change) were significantly different between the participant groups (CTS and control), but the keyboard used had no effect on these measures. The type of keyboard used affected participants' wrist position when typing. The CTS group rated the Kinesis keyboard as the most comfortable for the upper arm, forearm and wrist. The control group rated the Kinesis keyboard as the most comfortable for the forearm and wrist, but felt the standard keyboard was more comfortable for the upper arm. (The average comfort ratings, however, for both the Kinesis and standard keyboards fell between the scale points of None and Minimal, indicating little discomfort with these keyboards.) Although the differences were not statistically significant, the fastest reported typing speeds were those for the standard keyboards. Typing speed with the Kinesis was the slowest of the four keyboards. The analysis of ranks showed that both groups significantly preferred the traditional keyboards to the Kinesis.

Gerard, Jones, Smith, Thomas, and Wang (1994) measured initial learning rates and EMG activity while six participants typed with the Kinesis and standard keyboards. Participants practiced with each keyboard

for two hours (which included 24 five-minute trials with a one-minute break between each trial and a five-minute break every three trials). On a separate day, the participants used the keyboards again while the experimenters recorded EMG levels. The average typing speed for these participants on the standard keyboard was 73 wpm. After the 115 minutes of practice, the typists' speed with the Kinesis was 53 wpm, 72% of their speed with the standard. Their peak accuracy with the Kinesis was 97% of their accuracy with the standard. Gerard et al. did not report any statistical tests for differences in typing speed or accuracy. The EMG analysis showed that the muscle load (percent of maximum voluntary contraction) was consistently less with the Kinesis keyboard (an average difference of 2.0% across the four measured muscle groups, a statistically significant result).

The HCK Keyboard

The Health Comfort Keyboard is an adjustable (variable geometry) split keyboard. The only experimental data currently available for the HCK are those reported by Lopez (1993). (See the preceding section on the Kinesis keyboard for a description of this study.) For both the CTS and control groups, the HCK was the least comfortable keyboard for the upper arm, forearm, and wrist (with average comfort ratings for the HCK falling between the scale points of Minimal and Moderate). Although the differences were not statistically significant, the fastest reported typing speeds were those for the standard keyboards. Typing speed with the HCK was faster (but not statistically significantly faster) than that with the Kinesis. The analysis of ranks showed that both participant groups significantly preferred the traditional keyboards to the HCK.

Conclusions

The literature indicates two fairly clear effects of typing with split keyboards. First, typing speed is generally slower on split compared to standard keyboards. Second, EMG measurements typically show reduced muscle load in the wrist-forearm area for split relative to standard keyboards. Meta-analysis of the combined preference outcomes of the split keyboard experiments conducted from 1972 to 1993 has demonstrated that user preference across the studies is in favor of standard rather than split keyboards (Lewis, 1995b). Thus, it is difficult to interpret the typically lower EMG measurements for split keyboards. Part of the effect might be due to the difference in keyboard geometry resulting in lower static muscle contraction, but the effect might also be due in part to slower typing with split keyboards. Furthermore, the EMG evidence from Gerard et al. (1994) suggests that the EMG differences between split and standard keyboards, although consistent enough to produce statistical significance, might be too small to be of practical consequence (an average difference of about 2.0% of maximum voluntary contraction). The data from Lopez (1993) show a similar pattern for comfort ratings. Even though the Kinesis keyboard received better comfort ratings than the standard keyboard in Lopez's study, the average ratings for both the Kinesis and standard keyboards fell between rating points of None to Minimal discomfort. That alterations from standard keyboard geometry produce, at best, minimal impact on error rate, comfort, or fatigue, but typically cause an initial drop in typing speed, is consistent with preliminary results of a study of split keyboards recently conducted by the National Institute of Safety & Occupational Health (Naomi Swanson, personal communication, February 16, 1995).

Given certain environments and workstation configurations, split keyboards might enhance typing comfort, but with a probable reduction in typing speed for some unknown period of time. Rather than introducing a split keyboard into a workstation as an initial intervention for improving the comfort of a given typist, it might be simpler and more effective to enhance other environmental and physical features of the workstation. In any specific case of operator discomfort, an ergonomics specialist should evaluate the job and the total work setting.

54.5.2 Chord Keyboards

With traditional keyboards, typists press keys one at a time to create characters in sequence. Chord keyboards require the typist to press several keys simultaneously to input data (as in striking a chord on a piano). Because key combinations define the input, a chord keyboard requires fewer keys than a standard keyboard. For example, a five-key chord keyboard with binary switches could produce up to 31 (2^5 - 1) key combinations. A five-key chord keyboard with ternary (three-position) switches could produce up to 242 (3^5 - 1) key combinations. Two-handed chord keyboards allow for even more combinations. Some chord keyboards translate chords into phonemes and syllables; others translate the chords into single characters and numbers.

The most widely used chord keyboards are the Stenograph (patented in 1930) and the Palantype (patented in 1941). Typists who use these keyboards learn to as-

sociate chords with phonemes to produce syllables. This method of typing allows stenographers to develop very rapid input rates (fast enough to keep up with most talkers) with high speeds of around 250 to 300 words per minute (wpm), faster than a fast typist's speed of a little more than 100 wpm, but requires about three years for the acquisition of the skill (Beddoes and Hu, 1994). Beddoes and Hu reported work to develop a new chord stenograph keyboard (the minimum chord stenograph, or MCS), designed to be easier to learn. With the MCS, chords represent pairs of phonemes. Five people who learned the MCS typed, after 50 hours practice, from about 38 to 52 wpm. These typists needed from 2.5 to 11 hours to learn the MCS code. No data is yet available on how long typists must practice with the MCS to approach the speeds acquired by traditional stenographers.

Gopher and his colleagues have reported experiments with a two-handed chord keyboard designed for computer text entry (for example, Gopher, Hilsernath, and Raij, 1985; Gopher and Raij, 1988). The two halves of the keyboard were mirror images, connected in a lateral tilt arrangement. The chords for creating letters were the same on each half, and corresponded to the same fingers of each hand. Gopher and Raij conducted tests with people typing Hebrew text with a QWERTY-like keyboard (four participants), the chord keyboard with one hand (five participants), and the chord keyboard with two hands (six participants). They reported that participants learning the chord keyboard memorized the 23 character codes in about 30-45 minutes. Initial input rates for all conditions were about 7 to 8 wpm. After 25 hours of training, the reported typing rate for the chord keyboards was 32 wpm, while that for the QWERTY-like keyboard was 20 wpm. With extended practice (more than 25 hours), the participants using the two-handed keyboard produced faster keying than the other participants. One participant using the two-handed chord keyboard continued practicing for 60 hours and reached a rate of 59 wpm.

Most chord keyboards use two-position keys (resting or pressed). A number of researchers have recently studied a chord keyboard with three-position keys (resting, pushed away from the typist, or pulled toward the typist). The ternary chord keyboard (TCK) has eight keys, one for each finger. Callaghan (1991) studied the ease of activation of the 64 "simple" chords produced by the simultaneous movement of one finger from each hand. McMulkin and Kroemer (1994) had five people use a one-handed TCK to input 18 symbols (the ten digits and eight numeric functions) using 18 of the possible 24 two-finger chords. The participants needed an average of 34 minutes to learn the 18 chords with 97% accuracy. Their average initial typing rate was about 34.5 cpm (7 wpm). After 60 hours of practice, the average of each participant's fastest trial was 170 characters per minute (cpm), which roughly corresponds to 34 wpm. (The translation to wpm is imperfect because the stimuli were numbers rather than sentences and the participants typed using only 18 chords.) McMulkin and Kroemer reported that the function $\underline{CPM} = 34.5*(\underline{Trial}^{0.244})$ provided a good fit to the learning curve observed in their experiment.

In a similar study, Kroemer (1992) had two groups of people use two TCK prototypes (12 participants with TCK #2 and 10 with TCK #3). (Kroemer makes no mention of a TCK #1. TCK #3 was similar to TCK #2 for key type and placement, but had both keysets in one housing and provided fixed wrist rests for each hand.) The TCK #2 participants learned 58 of the 64 simple chords; the TCK #3 participants learned 59 of the simple chords. Participants needed from two to ten hours to memorize the chords. Experimental trials consisted of having participants type letters of the alphabet, numbers and punctuation. Initial typing rates with TCK #2 were about 30 cpm (6 wpm) and with TCK #3 were about 35 cpm (7 wpm). After 40 trials (about 10 hours), participants averaged about 75 cpm (15 wpm) with 97% accuracy. Despite the difference in number of chords learned (58 and 59 versus 18), this is comparable with the results reported by McMulkin and Kroemer. The function that McMulkin and Kroemer used to model their learning curve indicates that their typists produced an average of 85 cpm (17 wpm) at the 40th trial.

Lu and Aghazadeh (1992) reported a preliminary evaluation of the Infogrip Chordic Keyboard™ (ICK). The ICK is a two-handed binary chord keyboard consisting of a pair of 7-key keyboards, one for each hand. The fingers of a hand control four keys, and the thumb controls the remaining three. Four college students practiced typing 28 characters plus "space" and "return" for two hours with one hand. The participants needed an average of 108 minutes to learn the chords. The average initial typing rate was about 40 cpm (8 wpm). After two hours of typing the same sentence repeatedly, the average input rate was 49 cpm (10 wpm). This, too, is comparable to the results reported by McMulkin and Kroemer (1994), even though the keyboards and tasks were substantially different. Estimating from Kroemer (1992) and McMulkin and Kroemer, two hours of practice should correspond to about eight trials. The learning function provided by McMulkin and Kroemer indicates that their typists produced an average of 11.5 wpm at the eighth trial.

Conclusions

To draw reasonable conclusions from the experimental outcomes for chord keyboards, it would be valuable to have comparable data for the acquisition of skill with a standard keyboard, preferably collected using a large number of participants over a broad range of tasks, measuring speed and errors at least once per hour. Unfortunately, no such characterization seems to exist in the literature. The closest applicable data are those reported by Gopher and Raij (1988), but the sample size for their "standard" keyboard condition was only four participants typing Hebrew text. To compare typing acquisition gained with the sight method versus touch-typing, Book (1908, reported in Book, 1925) carefully studied the acquisition of typing skill by four participants (two participants per method). Problems with this study, however, are that the sample size was small, the minimum time period for analysis was the day rather than the hour, and the primary goal of the study was introspection about performance rather than quantification of performance. West (1956) evaluated the effectiveness of four types of practice as 345 airmen learned to type. After two hours of practice, their average typing rate ranged from 30 to 35 cpm (6 to 7 wpm). In a more recent study (Glencross and Bluhm, 1986), 241 participants learning to type with computer keyboards had an initial typing speed (after 90 minutes of training) of 35 cpm (7 wpm), increasing to about 70 cpm (14 wpm) after seven additional 45-minute practice sessions (a total amount of about 5 hours practice). This result for learning a standard keyboard is also comparable to the results reported by McMulkin and Kroemer (1994) for learning a chord keyboard. Estimating from Kroemer (1992) and McMulkin and Kroemer, five hours of practice should correspond to about 20 trials. The learning function provided by McMulkin and Kroemer indicates that their chording typists produced an average of 71 cpm (14 wpm) at the 20th trial. Certainly, there is a need for more research on both early and long-term typing with both chord and standard keyboards.

The information that is available indicates that beginning typists, both standard and chord, start with a typing speed of about 7 wpm. The learning curve reported by McMulkin and Kroemer (1994) seems to provide a reasonable characterization across the literature for the acquisition of chord typing (despite important differences between chord keyboards, number of chords, and material typed), with the exception of Gopher and Raij (1988). The one participant in Gopher and Raij's experiment who practiced for 60 hours attained a typing speed of 295 cpm (59 wpm). This was a particularly impressive performance given that the fastest participant in McMulkin and Kroemer (1994) achieved, during a comparable 60 hour practice period, a maximum speed of 186.3 cpm (37 wpm), only 63% of the maximum speed reported in Gopher and Raij. This variance in outcomes suggests that the human factors literature would benefit from an independent replication of Gopher and Raij, using both Hebrew and English text and using both binary and ternary chord keyboards.

The tasks in most chord keyboard evaluations have required participants to learn far fewer chords (in most cases, fewer than 30 chords) than keys typically present on a computer keyboard (about 90 to 100). Kroemer (1992) came the closest to a realistic assessment when requiring participants to learn 59 chords. Chord keyboard researchers typically do not assess chord retention or the use of chords for infrequently-used characters or functions. Because they allow such a rapid entry of data (given appropriate training), chord keyboards will continue to be the input device used by stenographers. Otherwise, chord keyboards are likely to see only limited application. For example, workers at the U. S. Post Office have used chord keyboards for mail sorting (Noyes, 1983a). (But see research by Richardson et al., 1988, showing a substantial advantage in training times for a calculator relative to a chord keyboard for entering zip codes. They did not report long-term performance data.)

As a final note on the topic, standard computer keyboards do require some simple chording with keys such as Shift, Alt, and Ctrl (for example, in the production of capital letters in lowercase mode). There are seven possible chording patterns with these three keys ($2^3 - 1$) which, combined with the remaining keys on a standard keyboard, allow the production of well over 500 characters and functions.

54.6 Conclusions

Although the modern standard keyboard reflects some design decisions initially made over 100 years ago, it also incorporates almost a century of subsequent research in typing and keying behavior. Proponents of the best-publicized alternatives to the standard keyboard (the Dvorak layout, split keyboards, and chord keyboards) have generally failed to provide convincing empirical cases for their wholesale replacement of the standard, although they might see reasonable application in certain special settings. A well-designed standard keyboard is an extremely effective data-entry device, and will probably remain a key component in human-computer interaction for the foreseeable future.

54.7 Acknowledgments and Trademarks

54.7.1 Acknowledgments

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54.7.2 Trademarks

The following are trademarks of the indicated companies: STR (Standard Telephon and Radio), Kinesis (Kinesis Corporation), Health Comfort and HCK (Health Care Keyboard Company, Inc.), and Infogrip Chordic Keyboard (Infogrip, Inc.).

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