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One-Handed Touch Typing on a QWERTY Keyboard

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ABSTRACT

"Half-QWERTY" is a new, one-handed typing technique designed to facilitate the transfer of two-handed touch-typing skill to the one-handed condition. It is performed on a standard keyboard with modified software or on a special half-keyboard with full-size keys. In an experiment using touch typists, hunt-and-peck typing speeds were surpassed after 3 to 4 hr of practice. Subjects reached 50% of their two-handed typing speed after about 8 hr. After 10 hr, all subjects typed between 41% and 73% of their two-handed speed, ranging from 23.8 to 42.8 words

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per minute (wpm). In extended testing, subjects achieved average one-handed speeds as high as 60 wpm and 83% of their two-handed rate. These results are important for providing access to disabled users and for designing compact computers.

1. INTRODUCTION

The QWERTY keyboard has been much maligned over the years. It has been called, by various authors "less than efficient" (Noyes, 1983, p. 269), "drastically suboptimal" (Gould, 1987, p. 16), "one of the worst possible arrangement[s] for touch typing" (Noyes, 1983, p. 267), "the wrong standard" (Gould, 1987, p. 23), and a "technological dinosaur" (Gopher & Raij, 1988, p. 601). Despite this, it has for various reasons (Litterick, 1981; Noyes, 1983; Potosnak, 1988) stood the test of time–a fact often overlooked by designers of alternative keyboards. Until recently, the massive skill base of QWERTY typists has been largely ignored, with new designs favoring "better" layouts. In this article, we are more conservative, preferring instead to argue that QWERTY is not an evolutionary dead end.

Our modern method of typing by touch was originally popularized by L. V. Longley and F. E. McGurrin in the latter part of the 19th century (Cooper, 1983). Curiously, despite more than 100 years of industrialization, QWERTY and the Longley and McGurrin technique remain largely unchanged. One of Longley's students would be comfortable on a modern computer keyboard, despite the alien machinery surrounding it. Similarly, we believe that this student would have little trouble acquiring the new, complementary, one-handed typing technique that we are about to propose. This article describes the new technique, with which a two-handed touch typist with very little retraining can type with one hand on a software-modified QWERTY keyboard. In effect, it is the one-handed equivalent of Longley and McGurrin's original eight-finger, two-handed typing technique. We call the technique *Half-QWERTY* because it uses only half of a QWERTY keyboard.

The present study examines the degree to which skill transfers from QWERTY to Half-QWERTY keyboards for typists already skilled in the use of a QWERTY keyboard. This was tested in an experiment using a standard keyboard for both the one-handed and two-handed conditions.

2. HALF-QWERTY CONCEPT[1]

Most one-handed keyboards are *chord*[2] keyboards. Half-QWERTY is not. The design builds on two principles:

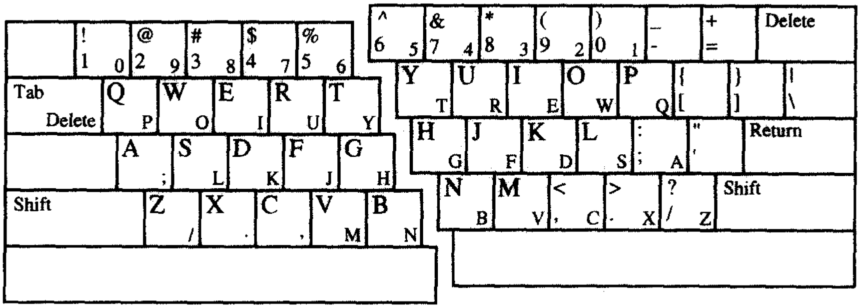
1. A user's ability to touch-type on a standard QWERTY keyboard.
2. The fact that human hands are symmetrical–one hand is a mirror image of the other–and the brain controls them as such.

A Half-QWERTY keyboard consists of all the keys used by one hand to type on a standard QWERTY keyboard, with the keys of the other hand unused or absent. When the spacebar is depressed, the missing characters are mapped onto the remaining keys in a mirror image (Figure 1), such that the typing hand makes movements homologous to those previously performed by the other hand. For example, in two-handed typing, the letter *J* is typed using the index finger of the right hand in the home row (see Figure 1, right side). Using the Half-QWERTY technique, *J* is entered with the left hand by holding down the spacebar and pressing the *F* key

1. U.S. Patent No. 5,288,158. European Patent No. 0,489,792. Australian Patent No. 647,750. Other patents pending. Half-QWERTY is a trademark of The Matias Corporation.

2. On chord keyboards, operators type by pressing one or more keys simultaneously. For example, pressing the *A* key types *A;* pressing the *B* key types *B;* pressing both keys simultaneously types some other arbitrary letter. Thus, a five-key chord keyboard can generate 31 different characters ($31 = 2^5 - 1$).

Figure 1. Left- and right-hand Half-QWERTY layouts on a standard QWERTY keyboard. When a key is depressed, the character in the upper left of the key is entered. When preceded by holding down the spacebar, the character in the lower right is entered. ***Note:*** **Copyright © 1992 by The Matias Corporation. Used with permission.**



(index finger of the left hand in the home row; see Figure 1, left side). Notice that in both cases the index finger is in the home row to type *J*. Thus, using the spacebar as a modifier, a typist can generate the characters of either side of a full-size keyboard using only one hand. We call this mirror-image remapping of the keyboard the *flip* operation.

2.1. Flip Operation

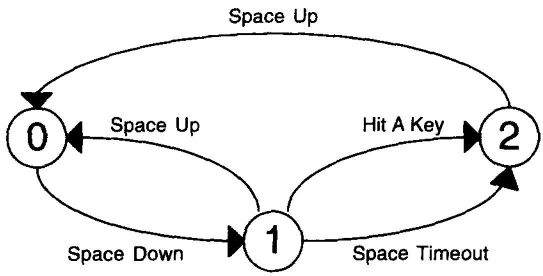
The flip operation consists of the following:

1. A spacebar capable of acting as a modifier key, in addition to its traditional role.
2. The mirror-image remapping of one half or both halves of a standard QWERTY keyboard, when the spacebar is depressed and held.

A state diagram governing the flip operation is shown in Figure 2. In State 0, the spacebar is up; in States 1 and 2, the spacebar is depressed. On a normal keyboard, depressing the spacebar generates a space character. If the spacebar is held down beyond a timeout value, space characters are generated repeatedly until the bar is released. Therefore, to generate one space, a typist depresses and releases the spacebar within a timeout value. Typing a space using Half-QWERTY works the same way. Depressing and releasing the spacebar within a timeout generates a space character.[3] In the state diagram, this corresponds to changing from State 0 to State 1 to State 0. In other words, if the spacebar is released while in State 1, a space is generated. This differs slightly from standard QWERTY. In QWERTY,

3. For this experiment, the timeout was 16/60 sec (or 267 msec).

Figure 2. **Spacebar state-transition diagram.** `if (state > 0) {key presses are flipped}; if (state == 1) {Space Up generates space character}.` ***Note:*** **Copyright © 1992 by The Matias Corporation. Used with permission.**



the space is generated on the depression of the spacebar; in Half-QWERTY, it is generated on the release.

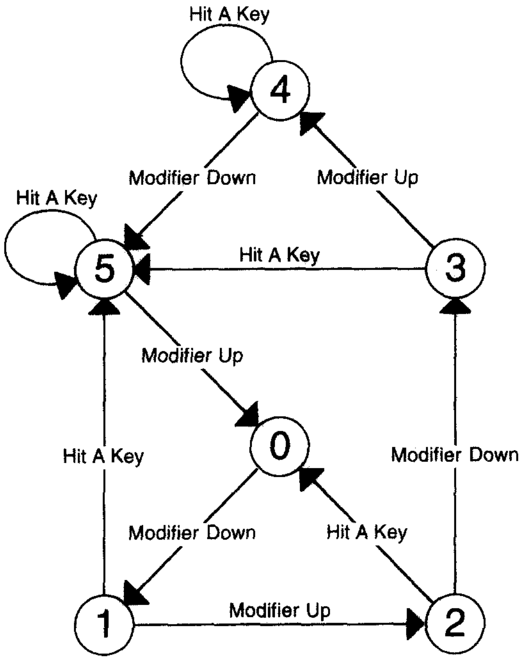
If a character key is struck while the spacebar is depressed (in State 1 or 2), that key is "flipped" (i.e., the mirror-image character is entered, and the state changes to 2–the "flip state"). While in State 2, the spacebar acts exactly like a modifier key: If a character key is struck, it is flipped; if the spacebar is released, the state returns to 0, and no space character is generated. State 2 is also the timeout state. If the user depresses the spacebar (State 1) and holds it down past the timeout value, the state changes to 2. The timeout serves to reduce the number of erroneous spaces generated as a side effect of using the spacebar as a modifier key. Occasionally, a typist depresses the spacebar with the intention of mirroring the state of another key but then changes his or her mind and releases the spacebar. Without the timeout, such actions would result in an unwanted space character. With it, the problem is alleviated.

We summarize the state diagram as follows. While in State 0 (the null state), the keyboard behaves as a QWERTY keyboard would. State 1 is ambiguous: It is not immediately clear whether a space character or the flipping of a subsequent key is desired. In State 2, the spacebar acts as a modifier key, flipping any character keys struck.

2.2. Modifier Keys

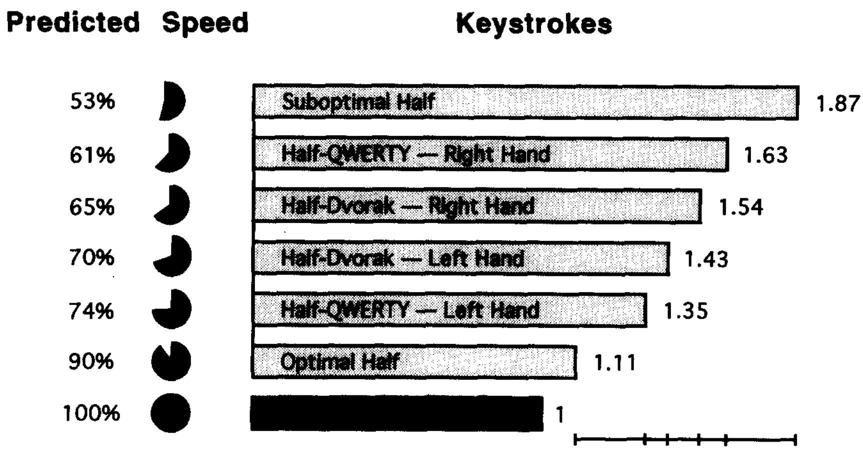
Modifier keys do not generate codes themselves but modify the code for a subsequent key struck while the modifier is active. Figure 3 shows the state diagram for the Shift key, as used in our experiment. If other modifier keys were implemented, they would behave in a similar manner. Odd-numbered states (1, 3, 5) indicate that the modifier key is depressed; even-numbered states (0, 2, 4) correspond to the release of the key. If the state is greater than 0, then the modifier key is active.

Figure 3. **Modifier-key state-transition diagram.** `If (state > 0) {modifier key is active}`. ***Note:*** **Copyright © 1992 by The Matias Corporation. Used with permission.**



On a regular keyboard, a modifier key is active when it is depressed and inactive when it is released. This corresponds to States 5 and 0, respectively, in Figure 3. If a character key is struck at any time while the modifier key is depressed (i.e., odd-numbered states), the state immediately jumps to 5, thus reverting to standard modifier-key behavior. In one-handed typing, however, it is convenient not to require continuous depression of a modifier key for it to be active. Therefore, we supply a "latch" mechanism, commonly known as *Sticky Keys.* Depressing and releasing a modifier key once (State 0 to 1 to 2) activate it for the next key struck. This is useful for capitalizing the first letter of a word, for example. Depressing and releasing the modifier key twice (State 0 to 1 to 2 to 3 to 4) lock it until it is unlocked by depressing and releasing it again (State 4 to 5 to 0). The lock is useful for capitalizing entire words. Thus, Sticky Keys allow one finger to do the work of several when performing key sequences that would otherwise require the simultaneous depression of two or more keys.

Figure 4. **Half-keyboard design space.**



2.3. Which Hand to Use?

Given the keyboard already described, we must now decide which hand is "best" for one-handed typing. In general, we believe it is the nondominant hand. This would free the more dexterous, dominant hand to use a mouse (or other device) to enter spatial information. Also, Provins and Glencross (1968) found that, for right-handed typists, the nondominant left hand performed as well as or better than the right hand. Therefore, generally we see no reason for using the dominant hand for one-handed typing. It is best saved for spatial input, to which it is better suited (Kabbash, MacKenzie, & Buxton, 1993).

2.4. Design Space

How optimal is Half-QWERTY? Or, stated differently, where does Half-QWERTY lie in the design space of possible half-keyboards? The design works by substituting extra keystrokes (depressions of the spacebar) for the presence of the other hand. Thus, a simple way of determining its efficiency is to calculate the number of additional keystrokes required for one-handed typing relative to two-handed typing. This is shown in Figure 4. The comparison is based on an analysis of the text file later used for our experiment. In the two-handed calculation, capitalized letters not preceded by another capitalized letter were counted as two keystrokes; all others counted as one. In each one-handed calculation, flipped characters not preceded by another flipped character were counted as two keystrokes; all others were counted as one; for capitalized letters, an extra keystroke was added.

A hypothetical optimal layout would require approximately 11% more keystrokes than two-handed typing, whereas a suboptimal layout would require about 87% more. By ***optimal,*** we mean a layout for which the 15 most frequently used letters–*e, t, a, o, n, r, i, s, h, d, l, f, c, m, u* (Pratt, 1942; Zettersten, 1978)–are nonflipped (one or two keystrokes); on a ***suboptimal*** layout, these letters would be flipped (as many as three keystrokes). Because our subjects would be using their (nondominant) left hand, Half-QWERTY typing would require 35% more keystrokes than two-handed typing. Of the layouts we have tested that were designed for two-handed typing, including several not shown in the figure, left-hand Half-QWERTY is the closest to being optimal. This is a happy accident, given that the QWERTY layout was not designed to support one-handed typing. Note, however, that this is only true of the left hand. Right-hand Half-QWERTY is considerably less efficient, requiring 21% more keystrokes than the left hand–63% more than two-handed typing. Thus, optimally, the left-hand layout should be used for Half-QWERTY typing.

Our calculations show that a ***balanced*** layout (one favoring neither left nor right hand) would require approximately 49% more keystrokes than two-handed typing. If we were to insert this value into our graph, we would find that it lies halfway between each of the left-hand and right-hand layouts shown. The line segment at the bottom of Figure 4 illustrates the symmetry of this relation. We can easily see the (predicted) performance trade-off between hands for a given layout. This also suggests that there is no such thing as a "perfect" keyboard layout. Those optimized for two-handed typing are less efficient for one-handed typing. Those favoring one hand handicap the performance of the other.

Finally, we extend this notion of extra keystrokes to predict roughly what percentage of two-handed speed a given one-handed typist can achieve. If the keystroke ratio of one-handed to two-handed typing is 1.35:1, we can take its reciprocal (1:1.35 = .74) as a basis for determining one-handed typing speed as a percentage of the two-handed rate. Thus, it should be possible for someone using a left-hand Half-QWERTY keyboard (typing in English) to achieve 74% of his or her two-handed typing speed. As we shall see, this is a fairly accurate baseline prediction.

2.5. Hand Symmetry, Critical Invariance, and Skill Transfer

Half-QWERTY is based on the principle that the human brain controls typing movements according to the finger used rather than the spatial position of the key. Thus, the finger used to press a key is the critical invariant–the critical similarity that is maintained across the training and transfer tasks–in the transfer of skill from QWERTY to Half-QWERTY. Lintern (1991) wrote:

> If critical invariants (specifically, those that pose a meaningful learning challenge) remain unchanged, [skill] transfer will be high even when many other features of the environment, context, or task are changed ... If an operator's perceptual sensitivity to critical invariants can be improved, that enhanced sensitivity will serve to facilitate transfer. (p. 262)

Our mirror-image encoding scheme (already described) follows from this, and our experimental procedure (to be described) was designed to enhance subjects' perceptual sensitivity to critical invariants.[4]

In the following section, we describe an experiment intended to test the degree to which skill transfers from QWERTY to Half-QWERTY keyboards among skilled touch typists.

3. SKILL TRANSFER EXPERIMENT

3.1. Method

Subjects. Ten right-handed, computer-literate QWERTY touch typists from a local university served as paid volunteers. Subjects used their nondominant (left) hand when typing with one hand. The Edinburgh Inventory (Olfield, 1971) was given to determine handedness. All subjects were self-acclaimed touch typists, and their first-session (two-handed) speeds ranged from 38 words per minute (wpm) to 74 wpm. The mean was 58 wpm.

Equipment. Tasks were performed on Apple Macintosh II computers running System 7 and using Apple (Model M0116) keyboards. A cardboard shield was placed between the subjects' hands and eyes to prevent them from looking at the keyboard.

A software package was developed that mimicked Typing Tutor IV,[5] with the subject's typing displayed beneath the input text (Figure 5). In addition to calculating speed and error rates, our software recorded complete keystroke-level data.

Procedure. Each subject participated in 10 sessions (no more than one session a day). Each session included a two-handed pretest, multiple blocks of one-handed typing, and a two-handed posttest. In addition, three subjects underwent prolonged testing. One subject participated in 20

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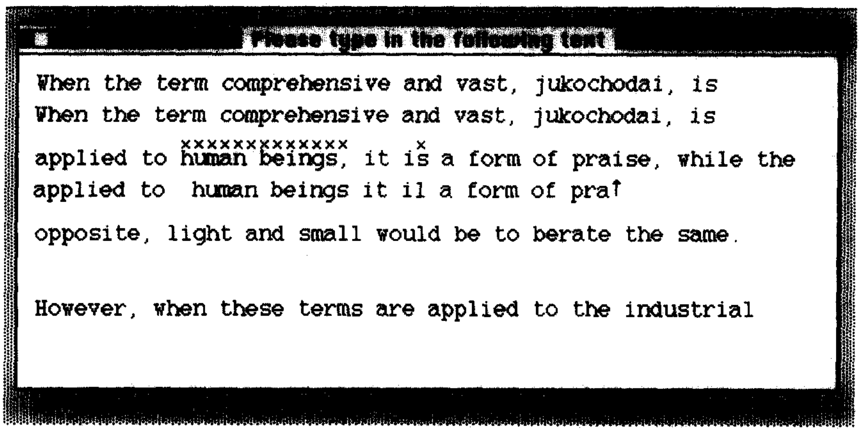
4. A rival encoding scheme is that of spatial congruence, which maintains that the spatial position of the key is the critical invariant. There is disagreement in the literature as to which of these schemes is "better." For a review of the relevant literature, see Matias, MacKenzie, and Buxton (1993).

5. Kriya Systems, Inc. Published by Simon & Schuster Software, Gulf+Western Building, One Gulf+Western Plaza, New York, NY 10023.

***Figure 5.* Screen snapshot of experiment software. Note that subjects must type in synchronization with the displayed text. Out-of-synchronization characters are treated as errors.**



sessions; two others participated in 40 sessions each. All one-handed typing was performed with the left hand, and subjects were not allowed to rest their right hand on the keyboard.

The Delete key was disabled so that subjects could not correct errors. A beep was heard for every error made. Subjects were instructed to type as quickly and accurately as possible while remaining in synchronization with the input text. They were also told to avoid long pauses of thought: If they were unsure of a given letter, they should guess and continue typing. Subjects could rest as desired between blocks.

The text for all typing was taken from a novel about Japanese-American relations. The text consisted of only uppercase and lowercase letters and simple punctuation (comma and period). This text differs from that of most of the typing studies we found in the literature, which tested lowercase typing only (Gopher & Raij, 1988; Grudin, 1983; Munhall & Ostry, 1983; Provins & Glencross, 1968).

The first session included special one-handed blocks designed to ease subjects into understanding the operation of the keyboard. These introductory blocks were performed after the two-handed pretest but before starting the regular one-handed typing task described earlier. In the first block, subjects typed whatever they pleased in order to familiarize themselves with the one-handed layout–particularly with the operation of the Shift key and of the spacebar timeout. After this practice block, subjects typed three blocks of text of gradually increasing complexity: left, right, and left-plus-right text blocks. For these blocks, the amount of mode switching was restricted in order to reinforce the idea that finger movements are homologously preserved in the transition from QWERTY to Half-QWERTY typing. The left block consisted of text entirely from the left side of a QWERTY keyboard, making it similar to two-handed typing but requiring only the left hand. Similarly, the right block consisted of only right-sided text. This required that the spacebar be held down continuously to mirror the layout of the keyboard. It was released only to type space characters. The left-plus-right block consisted of text of both types mixed together. Thus, for this block it was necessary to switch modes only between words that required it. Subjects were told that, when typing a right-sided word using the left hand, making the corresponding movement with their right hand is a helpful memory reference and that, if a mode error is made at the beginning of a word, the state of the spacebar must be changed to type the rest of the word correctly.

Design. The experiment was an investigation of the learning potential of the Half-QWERTY keyboard. Each 50-min session consisted of a series of text blocks typed by the subject. The block length was set to four lines of 60 characters in the first session (using Courier 14-point type) and was increased to six lines (and later eight lines) when subjects managed to type 30 or more one-handed blocks in one session. Subjects completed as many one-handed blocks as were possible in a session, ranging from 1 to 34 blocks, depending on speed and the amount of rest. Two-handed pretests and posttests were also given in order to test for interference effects of one-handed typing on two-handed typing.

The dependent measures were typing speed and error rate. Typing speeds are in wpm, and a word is defined as five characters (including spaces). Error rates are given as a percentage of total keystrokes (the lower the better). Subjects' typing was displayed beneath the input text, as consistent with Typing Tutor IV (Figure 5). Subjects had to type the correct character in the correct position. Thus, they had to type in synchronization with the text on the screen. If they fell out of synchronization, each out-of-synchronization character was counted as an error, resulting in what we later refer to as the *cumulative error rate.* This is contrasted with the *chunk error rate,* whereby consecutive errors are considered a single error. The basis for analyzing errors as such is expanded on later.

This strict interface was chosen for pragmatic reasons–specifically, the very large amount of data collected (more than 25 megabytes!) and the need to automate the data analysis. If subjects were allowed to type freely, the analysis would be extremely difficult to automate.

We collected complete keystroke-level data, which allowed detailed examination of interkey timings across states (Space Up, Space Down) and fingers, and of error patterns across letters and state sequences.

***Figure 6.* Mean performance scores for speed and accuracy on one-handed (1H) and two-handed (2H) typing over 10 sessions.**

Session	Speed (wpm)		Cumulative Errors (%)		Chunk Errors (%)		Chunk-Adjusted Speed (wpm)	
	1H	2H	1H	2H	1H	2H	1H	2H
1	13.2	58.3	15.16	3.44	12.22	2.19	11.7	57.0
2	18.2	59.5	10.90	3.55	9.00	2.20	16.6	58.3
3	21.1	62.1	8.74	2.53	7.36	1.64	19.6	61.2
4	24.4	61.4	8.50	3.11	7.14	2.16	22.7	60.2
5	27.1	63.5	7.99	3.52	6.68	2.30	25.4	62.1
6	29.1	62.9	7.69	3.59	6.32	2.31	27.3	61.6
7	30.6	63.6	6.82	3.67	5.73	2.15	28.9	62.3
8	31.6	64.5	7.40	3.58	5.87	2.14	29.8	63.1
9	33.6	66.1	7.28	3.30	5.83	1.90	31.7	65.0
10	34.7	65.0	7.36	4.14	5.77	2.68	32.7	63.4

3.2. Results

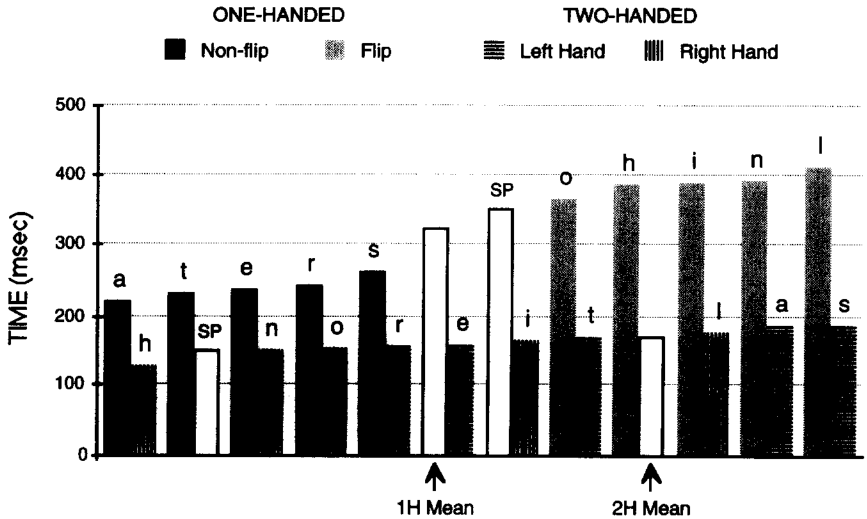
Subjects were able to adapt to Half-QWERTY typing very quickly. As shown in Figure 6, Session 1 resulted in an average speed of 13.2 wpm with more than 84% accuracy. This performance is impressive, especially considering how little training was given. For instance, subjects were not required to memorize the layout before starting the one-handed typing task and therefore had to rely entirely on skill transfer from two-handed typing. One-handed speed improved significantly over the 10 sessions, $F(9, 81) = 77.9$, $p < .0001$, to reach a 10th-session average of 34.7 wpm. Improvement in the one-handed cumulative error rate was also statistically significant, $F(9, 81) = 13.4$, $p < .0001$, dropping to an average of 7.36% errors in the 10th session.[6] This is less than twice the rate of errors made in two-handed typing. (The distinction between cumulative and chunk errors is drawn later.)

Worthy of note is that two-handed typing speeds improved significantly over the 10 sessions, $F(9, 81) = 4.57$, $p < .0001$. This is likely due to subjects' getting accustomed to the software and the feel of the keyboard. One-handed typing might also have had an effect. There was no significant reduction in two-handed cumulative error rates over the 10 sessions, $F(9, 81) = 1.02$, $p > .05$.

The two-handed scores just given are the aggregate of the pretests and posttests. However, if we analyze them separately, we find that one-

6. These rates differ slightly from those reported in Matias et al. (1993). Matias et al.'s rates were artificially inflated due to a software error in the first several sessions. Note, as well, that the error-rate data underwent an arcsine transformation before the analysis of variance. This technique stabilizes the variances when data are proportions (Winer, 1971, p. 400).

Figure 7. **Mean key times of the 11 most frequently occurring characters in Session 10.**



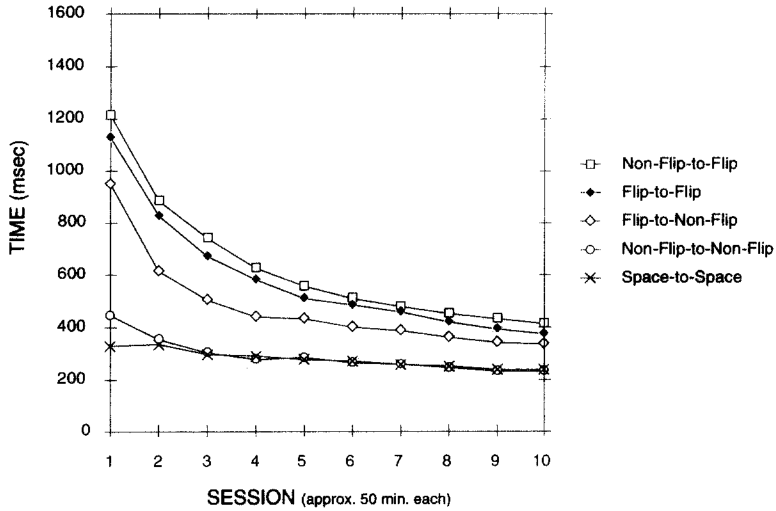
handed typing did affect two-handed performance, though not by much. The mean pretest speed over the 10 sessions dropped slightly from 63.8 wpm to 62.1 wpm in the posttest. This drop was statistically significant, $F(1, 9) = 8.64, p < .05$, and we attribute it to interference and fatigue from 40+ min of one-handed typing. Two-handed error rates were similarly affected: Cumulative errors rose from 2.79% to 4.10%, $F(1, 9) = 11.6, p < .01$.

Temporal Analysis

Figure 7 shows the mean one-handed and two-handed key times for the 11 most frequently occurring correctly typed characters in Session 10 in order of decreasing speed. Despite similarities in technique, we see that, from a temporal perspective, one-handed typing is very different from two-handed typing. In particular, the rank order of individual times is different. Although two-handed times seem fairly evenly distributed between the left and right hands, one-handed typing clearly favors nonflipped characters. The fastest one-handed times were for nonflipped characters, followed by the space character, with flipped characters being the slowest. If we consider these three classes of characters in context, we can see how this speed trend develops over the 10 sessions. Figures 8 and 9 show the interkey times by class for the 10 sessions.

Figure 8 is as we would expect. Nonflipped characters were typed faster than flipped characters for all 10 sessions, and transitions were quickest if the preceding character was nonflipped. This is understandable given that

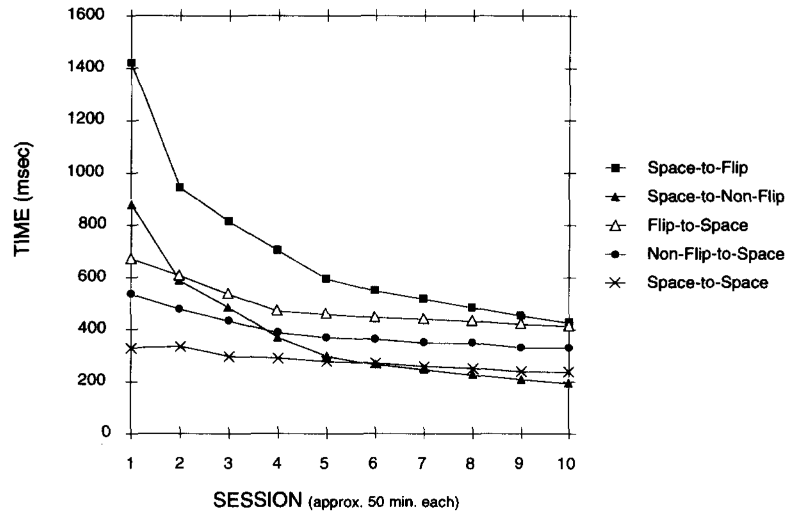
***Figure 8.* Interkey times illustrating the degree of skill transfer/acquisition in flip and nonflip conditions.**



flipped characters require one or two keystrokes, whereas nonflipped characters require only one. However, improvement over the 10 sessions was greatest for flipped characters. The mean interkey time for flip-to-flip transitions went from 1,126 msec in Session 1 to 374 msec in Session 10 (less than one third of Session 1 time). Thus, initial skill transfer was greatest for nonflipped characters, but improvement was greatest for flipped characters. Figure 8 also highlights some key differences between one-handed and two-handed typing. Among expert two-handed typists, the fastest interkey times are those occurring between hands (Gentner, 1983). In one-handed typing, the opposite is true–these transitions are the slowest (nonflip to flip) because they require an additional keystroke (depression of the spacebar) and are performed using a single hand. One-handed typing does not allow as much paralleling of actions as two-handed typing does. A two-handed typist can parallel movements between hands and among the fingers of each hand (eight fingers plus thumb); a one-handed typist can parallel only movements among the fingers of one hand (four fingers plus thumb). Thus, the difference between one-handed and two-handed rates will likely be greater for fast two-handed typists than for slower two-handed typists. As we shall see, this is indeed the case.

Figure 9 shows the mean interkey times for transitions involving the space character. There is a very interesting dynamic at play here, because space characters are issued later than the others–at the release of the key rather than when it is pressed. The delayed space causes an imbalancing

***Figure 9.* Effects of delayed space character on interkey times. Second slowest time in Session 1 is fastest time in Session 10.**



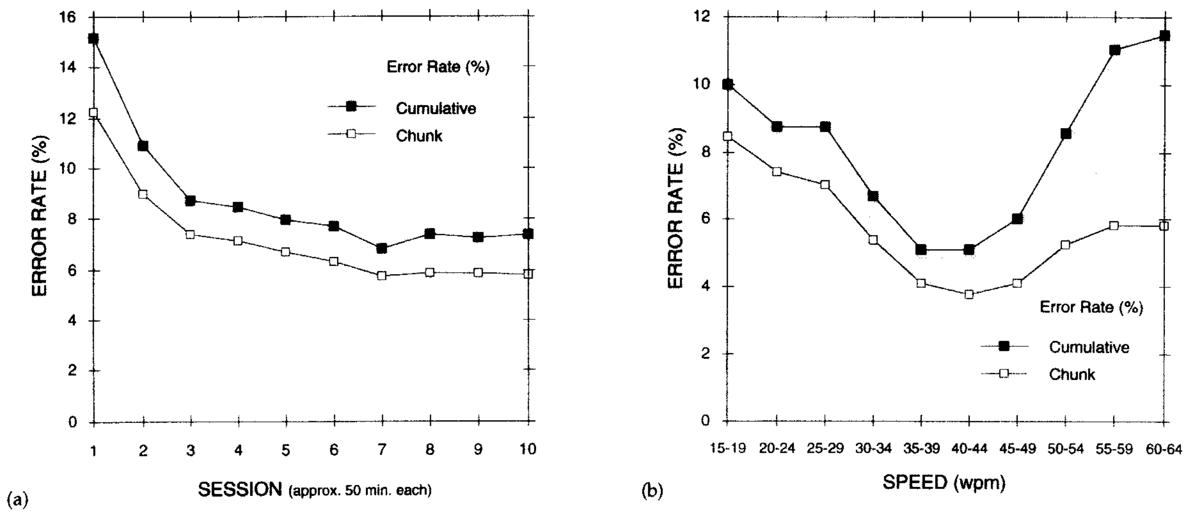
effect that results in the second slowest transition (space to nonflip) in Session 1 becoming the fastest transition in Session 10.

Error Analysis

The error rates in this experiment were quite high compared to those reported by researchers testing other types of keyboards–namely, QWERTY (Grudin, 1983) and chord (Gopher & Raij, 1988). We believe this is due to the nature of the task being tested (viz., skill transfer). Half-QWERTY typing lends itself very well to "educated guessing" by QWERTY typists. The side effect is higher error rates. If an entirely new layout were being taught (as in previous studies), guessing would not be viable–key positions would have to be memorized in advance. This was not the case in our study. Subjects did not memorize the layout before starting the experiment. They relied entirely on skill transfer–hence the higher rates. However, there was another factor that tended to inflate our error scores–the definition of an error.

Our software displayed subjects' typing beneath the input text. In addition to typing the text correctly, subjects had to type in synchronization with the input text already displayed. If they fell out of synchronization, each out-of-synchronization character was counted as an error, resulting in a higher reported error rate. This effect can be compensated for by grouping errors into chunks (i.e., counting only the first error when bursts of two or more errors occur in succession). As Figure 10a shows, this chunk error rate is lower than the cumulative rate previously cited. Fur-

Figure 10. **Mean error rates (a) by session and (b) by speed. The difference between cumulative and chunk error rates increases with speed.**



thermore, the effect increases with speed, as seen in Figure 10b. As a subject's typing speed rises, more errors are made before the subject can react, resulting in even higher cumulative error rates. Notice that, after subjects got above 39 wpm, the difference between the cumulative and chunk error rates (shaded) started to increase. In the 60- to 64-wpm range, the cumulative rate was double the chunk error score.[7] Because subjects could not correct errors, we believe that the chunk error rate is a more appropriate measure of the errors that occurred.

Speed Analysis

Because our error analysis revealed that error rates increased with speed, there might be a speed–accuracy trade-off at work here. A simple and logical method of compensating for this is to reduce the speed in proportion to the number of errors that occurred. In other words, take the standard wpm score and multiply it by 1 minus the error rate. This adjustment penalizes inaccurate typists more severely than accurate typists.

Figure 11 shows subjects' one-handed speeds, adjusted using the chunk error rate. Performances varied a great deal among subjects. For example, Subject 6 averaged 16.0 wpm in Session 1. Subject 7 did not reach a comparable speed until Session 4. Many factors likely contributed to this, but key among them is subjects' individual two-handed skill levels. Figure 12 shows subjects' one-handed and two-handed speeds and their ratio for Sessions 1 and 10. Notice that, by Session 10, subjects with high two-handed scores were typing at a lower percentage rate than the slower two-handed subjects. This is what we predicted would happen. Fast two-handed typists were not able to transfer as much of their skill as slower typists were because their two-handed training exceeded what was transferable to one-handed typing (between-hand paralleling of movements, etc.).

Finally, it is worth noting that none of the subjects had peaked by Session 10, even though three of them were typing in the 40-wpm range. Also, none of the subjects reached the earlier predicted peak of 74% of their two-handed rate, although Subject 9 came very close. More testing is required to determine long-term potential.

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7. The error rates shown in Figure 10b are the one-handed rates for Session 5 onward and include the data obtained from extended subject testing. Note also that this figure pools the data across subjects and sessions with, of necessity, no balancing, because typing speed is the independent variable. Thus, readers are cautioned not to overinterpret the results of this figure. For example, much of the data at the high typing rates might have come from only one or two subjects whose attention to errors was atypical.

Figure 11. **One-handed chunk-adjusted typing speed by subject and session.**

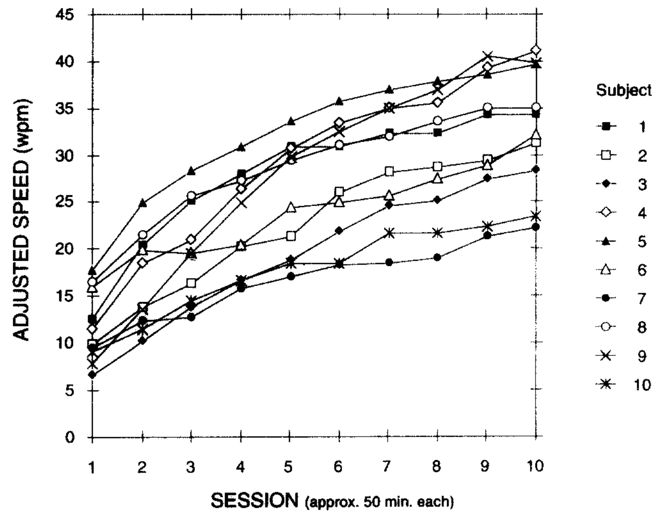
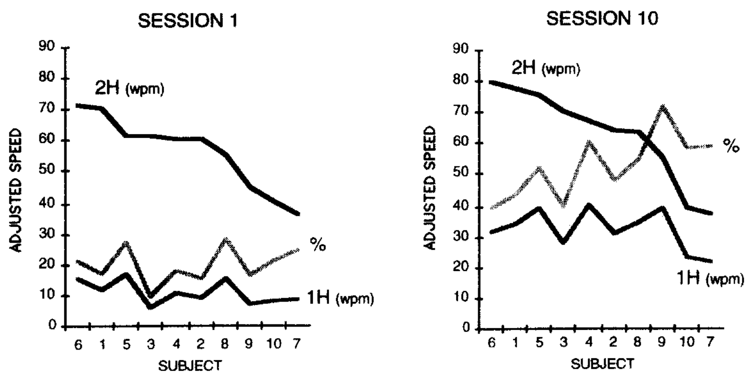


Figure 12. **One-handed and two-handed chunk-adjusted speeds and their ratio by subject for Sessions 1 and 10. Notice that, by Session 10, subjects with high two-handed scores were typing at lower percentage rates than the slower two-handed subjects.**



3.3. Discussion

Using the unadjusted data, subjects on average exceeded hunt-and-peck typing speeds after about 3 to 4 hr. Wiklund, Dumas, and Hoffman (1987) found an average speed for one-handed hunt-and-peck typing on a standard keyboard of approximately 23 wpm. Performances on the different compact keyboards were considerably worse. They ranged from 15 to 21 wpm, depending on key type, size, and spacing. Our subjects were typing in this range after less than 2 hr of practice and exceeded 50% of their two-handed speed after about 8 to 9 hr of use. This is comparable to Wiklund et al.'s measure of average handwriting speed (33 wpm). By Session 10, subjects were typing between 41% and 73% of their two-handed speed, ranging from 23.8 to 42.8 wpm. These fast learning rates were possible because our subjects were able to take advantage of previously learned touch-typing skills.

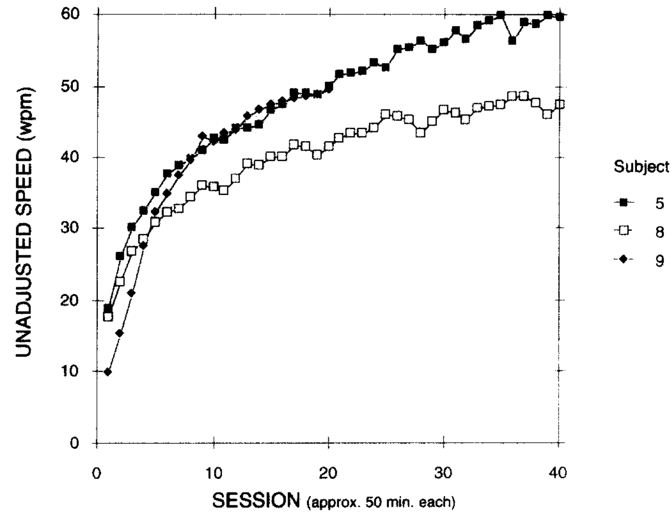
Another alternative for one-handed typing is a one-handed chord keyboard. Gopher and Raij (1988) tested subjects' rate of skill acquisition on both one-handed and two-handed chord keyboards as well as on the standard QWERTY keyboard. None of their subjects had any previous experience in typing. After 10 hr, their one-handed group was typing at approximately 21 wpm. This compares to the Half-QWERTY subjects' Session 10 average of 34.7 wpm. Gopher and Raij's subjects did not reach comparable rates until Session 29–three times as long. Again, the Half-QWERTY subjects were at an advantage due to previous training.

Extended Sessions

In their analysis of one-handed and two-handed chord keyboard typing, Gopher and Raij (1988) found that, until about Session 25, two-handed performance was only slightly better than one-handed performance. This begs an interesting question: What percentage of two-handed speed can be achieved with one hand by an expert Half-QWERTY typist? Our keystroke calculation has already shed some light on this question, but the 10 sessions performed by each subject were insufficient to reach the rate predicted. Thus, several weeks after the initial tests, we invited three of our original subjects back for more trials. They were chosen based on their performances relative to that of the other subjects (with Session-10 unadjusted speeds for one and two hands given, respectively, in parentheses). Subject 5 was chosen for being among the fastest of those tested (42.5 and 78.1 wpm). He was a graduate student who typed an average of 1 to 2 hr a day. Subject 8 was chosen for being close to the average (35.8 and 64.6 wpm). He was an undergraduate who typed 30 min a day on average. Subject 9 was chosen for being among the fastest one-handed typists but having a lower than average two-handed speed (42.2 and 58.1 wpm). Also an undergraduate, she typed an average of 1 hr a day. None of the three subjects had ever typed "professionally."

Figure 13 shows the (unadjusted) one-handed speeds recorded for our three extended subjects. By Session 40, Subject 8 was typing more than 47 wpm. This contrasts with Subject 9's achievement of comparable speeds in half that time–49.4 wpm by Session 20. However, Subject 5 managed to outperform them both, attaining approximately 60 wpm by Session 40.

***Figure 13.* Extended testing: Unadjusted one-handed speed (wpm) by subject and session.**

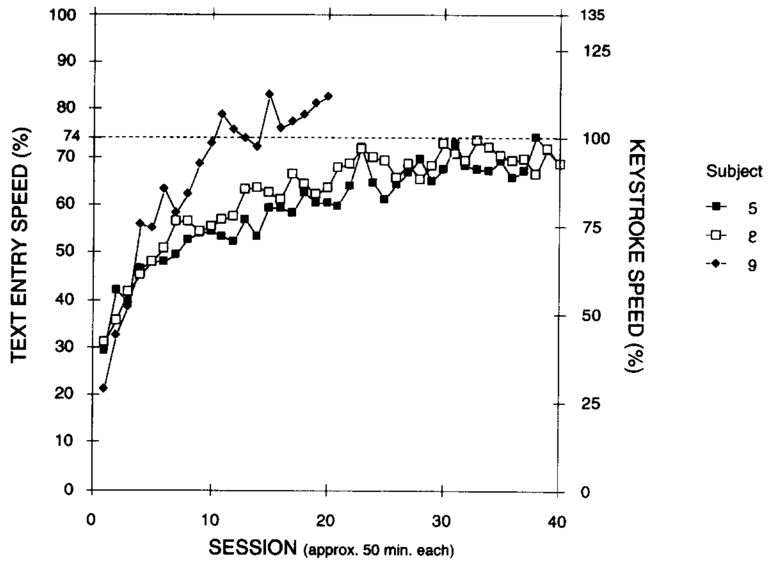


This subject's fastest block was 64 wpm, which is quite fast, even by two-handed standards.

Next, we consider one-handed speeds as a percentage of two-handed performance. Figure 14 shows the extended subjects' mean speed ratios, with a dotted line indicating the leveling-off point predicted by our keystroke calculation. By Session 20, Subjects 5, 8, and 9 were typing at 60.4%, 63.5%, and 82.6% of their two-handed rates, respectively. By Session 40, Subjects 5 and 8 were typing at 68.5% and 68.6%, respectively, and appeared to be leveling off where predicted–at 74% of their two-handed speed. However, this may be deceptive. For a skill requiring as much training as typing does, 40 sessions is minimal. After weeks, months, years of practice, it is possible that these subjects could surpass 74%. Subject 8 came very close, Subject 5 actually achieved it (in Session 38), and Subject 9 beat the prediction in only 11 sessions. Similarly, changes in levels of two-handed skill might greatly affect these scores. For reasons already discussed, one-handed rates level off at lower wpm scores than two-handed rates. Thus, for example, if Subject 9 were to undergo two-handed training, her one-handed speed would not likely increase in equal proportion to her two-handed rate. Subsequent two-handed speed increases would be due (in part and increasingly) to greater between-hand and among-finger paralleling of movements, only the latter of which is transferable to one-handed typing. Therefore, 74% must remain only a baseline prediction.

The unstated assumption in our keystroke calculation is that every keystroke is like every other. As our analysis of interkey times showed, this

Figure 14. Extended testing: Unadjusted ratio of one-handed speed as a percentage of two-handed speed. The text-entry–speed scale shows the (net) speed according to the amount of text produced (output). The keystroke-speed scale indicates the actual (gross) keystrokes performed to produce that text (input).



clearly is not the case. Some keystrokes are faster than others. Thus, we need a better model–preferably one that accounts for individual differences among typists. Now we present a model that attempts to address these concerns.

Modeling Expert Performance

The following model predicts the approximate expert-level performance of a given one-handed typist relative to his or her two-handed speed. For this model to give a meaningful result, the typist must have achieved a mean one-handed speed near or greater than 74% of his or her two-handed rate.[8]

Subjects typing near peak one-handed speeds were tested in both one-handed and two-handed typing for a given length of time. For each subject, we then created four 55 × 55 matrices with cells corresponding to every possible interkey transition.[9] In one matrix, we recorded the number

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8. Seventy-four percent is the prediction shown in Figure 4 for subjects typing on the left-hand Half-QWERTY layout. If the right hand or another layout were used, the minimum percentage required by the model would be different.

9. The 55 rows and columns include one for each letter of the alphabet, both uppercase and lowercase (52), and the comma, period, and space characters.

of occurrences of each one-handed interkey transition (correctly) typed. In another, we recorded the fastest time for each one-handed transition (correctly) typed. We then multiplied the value of each cell in one matrix by its corresponding value in the other matrix, summed the results, and divided by the total number of keystrokes. This gave us the mean one-handed interkey time if all keystrokes were typed correctly and at their maximum speed. We repeated this procedure for two-handed typing and then took the ratio. This ratio of mean fastest interkey times is the one-handed speed predicted to be attainable by a given subject as a percentage of two-handed speed.

We calculated the ratio of predictions for the three subjects who underwent extended testing. Using the data from Sessions 35 to 40, our model predicted that Subject 5 would eventually achieve approximately 77% of his two-handed rate (68 msec / 88 msec = 77% = 66 wpm). Given that this subject was able to type individual blocks as fast as 64 wpm, our prediction seemed reasonable. For the same sessions, Subject 8 gave a ratio of 82% (106 msec / 130 msec = 82% = 56 wpm). This might have been a little optimistic. The subject, however, did get fairly close to 50 wpm, so 56 wpm might be possible. Subject 9's spectacular performance is by no means diminished by this model. Based on the data from Sessions 18 to 20, the model predicted that this subject would one day achieve a staggering 91% of her two-handed rate (116 msec / 128 msec = 91% = 55 wpm). Indeed, it is a shame that she participated in only 20 sessions. Her fastest block was at 88% of her two-handed rate–fairly close to our model's prediction. We now consider the reasoning behind our new model.

Our model is based on the assumption that, as typists approach their peak one-handed speed,[10] the ratio of their mean one-handed to two-handed speeds approaches the ratio of their mean fastest interkey times (calculated earlier).

As mean 1H speed → PEAK,

$$\frac{\text{mean 1H speed}}{\text{mean 2H speed}} \rightarrow \frac{\sum_{i=1}^{55}\sum_{j=1}^{55}[(\text{fastest 2H time})_{ij} \times n_{ij}]}{\sum_{i=1}^{55}\sum_{j=1}^{55}[(\text{fastest 1H time})_{ij} \times n_{ij}]}$$

where n_{ij} is the frequency of each individual interkey transition $_{ij}$.

Our model further assumes that the fastest times will peak well before the mean one-handed speed does. Thus, for subjects typing near peak

10. By ***peak one-handed speed,*** we mean the peak relative to the current two-handed speed. Higher two-handed speeds, achieved through additional training, would likely result in a corresponding increase in one-handed speed and possibly vice versa.

one-handed speeds (i.e., near the 100% keystroke rate), the ratio of the mean fastest times is assumed to be approximately equal to the eventual peak ratio of the mean speeds.

None of the subjects reached the performance levels predicted by our model, but that was expected. It is likely that months or years of practice are required for one-handed skills to reach their ultimate potential.

Skill Transfer Between Hands and Flip Inversion

Another issue to consider is how difficult it is to switch from typing with one hand to typing with the other, especially after long-term training. During the evaluation of a one-handed chord keyboard, Rochester, Bequaert, and Sharp (1978) trained one student using the right hand only. The subject was later retrained to type with the left hand only. The subject "reached close to his right-hand typing speed in less than one third the time he spent learning right-handed typing" (p. 62). It is not known how a Half-QWERTY typist would perform under similar conditions. However, such a typist might be even further impeded by the effects of "flip inversion," to be described.

On the dual QWERTY/Half-QWERTY keyboard shown in Figure 1, left-hand Half-QWERTY typing is different from right-hand typing–the use of the spacebar for flipping the layout is inverted. For example, the left hand *E* is typed by striking the *E* key (one keystroke); with the right hand, Space-*I* is struck to type *E* (two keystrokes). This inverting affects the entire layout. Informal tests have shown that flip inversion can be compensated for with extra concentration, but the additional cognitive load yields higher error rates and slower speeds. An alternative approach is to invert the layout in advance in order to compensate for this effect. More study is required.

4. DESIGN IMPLICATIONS

The major design implication of our research is that it is now possible to touch-type with one hand, using any standard QWERTY keyboard that is under computer control. This can be achieved entirely in software, thus obviating the need for specialized hardware. Finally and most important, if the user is a trained two-handed touch typist, those skills will be transferred, thus minimizing learning time. Now we briefly discuss a few applications of the design. For more details, see Matias, MacKenzie, and Buxton (1993, 1994).

Using a Half-QWERTY keyboard in one hand and a pointing device such as a mouse in the other recaptures the two-handed flavor of Engelbart and English's (1968) system (also see Buxton & Myers, 1986). Text is entered with one hand, and items are selected and manipulated with the other. Because both hands are in the home position for their respective

Figure 15. **Prototype wearable computer. The actual computer is carried in a waist pouch. An LCD screen is worn on the wrist of the nondominant hand (the wristwatch wrist), and a Half-QWERTY keyboard is worn on the other wrist. The resulting typing posture allows the user to type and view the screen simultaneously.** ***Note:*** **Copyright © 1994 by Edgar Matias. Used with permission.**

tasks, no time is lost moving the hands between devices. In an experiment using a mouse and QWERTY keyboard, Douglas and Mithal (1994) found that homing time accounted for 28% of the total time spent pointing, homing, and typing. By implementing Half-QWERTY on a standard keyboard, one can easily switch between this type of input and two-handed typing. Finally, because each side of the keyboard is mapped onto the other side when the spacebar is depressed, either hand can be used for one-handed typing.

A computer that is worn, rather than held, has potentially significant advantages for data collection "in the field." By modifying a Hewlett–Packard 95LX palmtop computer, we were able to construct a prototype wearable computer (Figure 15). The prototype allows data to be entered without the need of a table or other supporting surface. Typing can be performed while standing or even walking. This prototype was on display at a recent Computer–Human Interaction conference (Matias et al., 1994), during which the operator wore it on 4 consecutive days over time periods varying from 4 to 9 hr. Because the operator rested his arms at his sides when not demonstrating the unit (which itself was fairly light), he felt no premature arm strain.

With media reports of repetitive stress/strain injuries (RSI) increasing (Adler, Leonard, Namuth, & Hager, 1992; "Key Decisions," 1993), Half-QWERTY can potentially allow some users to start typing again. Because RSI does not always occur in both arms, users with one good hand could adopt the Half-QWERTY technique, as could amputees and hemiplegics. For the presently uninjured, the option of typing with one hand or two may reduce the likelihood of users remaining in one fixed typing posture for long periods of time. Periodic one-handed typing may have the effect of creating a "virtual typing break," shifting the workload around for a while and getting the blood flowing. Also, when typing one-handed, the wrists are not bent as they often are in two-handed typing. This bending of the wrists toward the little finger is called *ulnar deviation* and is one of the known causes of RSI. However, periodic breaks are still advisable to reduce the risk of injury. Because one-handed typing requires more keystrokes (i.e., more work) than two-handed typing, and it is being performed entirely with the one hand, special care should be taken not to overload the one-handed-typing hand. More study is required.

Finally, our results may also have implications for numeric-keypad operators. Users skilled in number-pad touch typing, who (whether due to injury or some other reason) wish to transfer their skill to the other hand would probably find a mirror-image numeric keypad effective.

5. CONCLUSIONS

We have shown that it is possible for QWERTY typists to achieve high one-handed typing rates (40+ wpm) in a relatively short period of time (< 10 hr) using the Half-QWERTY technique. These speeds are two to three times the rates achievable using compact keyboards and exceed handwriting speeds. These high learning rates are due to the transfer of two-handed skill through Half-QWERTY's mirror-image hand-to-hand mapping scheme.

These results lead to new possibilities for human–computer interfaces. For example, it is now possible to build a practical wearable computer. Because the design can also be implemented in software, wide and convenient access to one-handed typing is possible on a standard keyboard. These findings are especially important for designers of systems for disabled users and of compact computing systems.

NOTES

Background. This article is an extension of work that first appeared in Matias, MacKenzie, and Buxton (1993).

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REFERENCES

Adler, J., Leonard, E. A., Namuth, T., & Hager, M. (1992, December 7). Typing without keys. *Newsweek*, pp. 63–64.

Buxton, W., & Myers, B. (1986). A study in two-handed input. *Proceedings of the CHI '86 Conference on Human Factors in Computing Systems*, 321–326. New York: ACM.

Cooper, W. E. (1983). Introduction. In W. E. Cooper (Ed.), *Cognitive aspects of skilled typewriting* (pp. 1–38). New York: Springer-Verlag.

Douglas, S. A., & Mithal, A. K. (1994). The effect of reducing homing time on the speed of a finger-controlled isometric pointing device. *Proceedings of the CHI '94 Conference on Human Factors in Computing Systems*, 411–416. New York: ACM.

Engelbart, D., & English, W. K. (1968). A research center for augmenting human intellect. *Proceedings of the Fall Joint Computer Conference*, 395–410. Washington, DC: Thompson.

Gentner, D. R. (1983). Keystroke timing in transcription typing. In W. E. Cooper (Ed.), *Cognitive aspects of skilled typewriting* (pp. 95–120). New York: Springer–Verlag.

Gopher, D., & Raij, D. (1988). Typing with a two-handed chord keyboard: Will the QWERTY become obsolete? *IEEE Transactions on Systems, Man, and Cybernetics, 18,* 601–609.

Gould, S. J. (1987, January). The panda's thumb of technology. *Natural History,* pp. 14, 16, 18–20, 22–23.

Grudin, J. T. (1983). Error patterns in novice and skilled transcription typing. In W. E. Cooper (Ed.), *Cognitive aspects of skilled typewriting* (pp. 121–143). New York: Springer–Verlag.

Kabbash, P., MacKenzie, I. S., & Buxton, W. (1993). Human performance using computer input devices in the preferred and non-preferred hands. *Proceedings of the INTERCHI '93 Conference on Human Factors in Computing Systems,* 474–481. New York: ACM.

Key decisions. (1993, April 3). *The Economist,* pp. 78–79.

Lintern, G. (1991). An informational perspective on skill transfer in human–machine systems. *Human Factors, 33,* 251–266.

Litterick, I. (1981, January 8). QWERTYUIOP–Dinosaur in a computer age. *New Scientist,* pp. 66–68.

Matias, E., MacKenzie, I. S., & Buxton, W. (1993). Half-QWERTY: A one-handed keyboard facilitating skill transfer from QWERTY. *Proceedings of the INTERCHI '93 Conference on Human Factors in Computing Systems,* 88–94. New York: ACM.

Matias, E., MacKenzie, I. S., & Buxton, W. (1994). Half-QWERTY: Typing with one hand using your two-handed skills. *Companion of the CHI '94 Conference on Human Factors in Computing Systems,* 51–52. New York: ACM.

Munhall, K. G., & Ostry, D. J. (1983). Mirror-image movements in typing. In W. E. Cooper (Ed.), *Cognitive aspects of skilled typewriting* (pp. 247–257). New York: Springer–Verlag.

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

Olfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologica, 9,* 97–113.

Potosnak, K. M. (1988). Keys and keyboards. In M. Helander (Ed.), *Handbook of human–computer interaction* (pp. 475–494). Amsterdam: Elsevier.

Pratt, F. (1942). *Secret and urgent: The story of codes and ciphers.* Garden City, NY: Blue Ribbon.

Provins, K. A., & Glencross, D. J. (1968). Handwriting, typewriting and handedness. *Quarterly Journal of Experimental Psychology, 20,* 282–320.

Rochester, N., Bequaert, F. C., & Sharp, E. M. (1978, December). The chord keyboard. *Computer,* pp. 57–63.

Wiklund, M. E., Dumas, J. S., & Hoffman, L. R. (1987). Optimizing a portable terminal keyboard for combined one-handed and two-handed use. *Proceedings of the Human Factors Society 31st Annual Meeting,* 585–589. Santa Monica, CA: HFS.

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

Zettersten, A. (1978). *A word-frequency list based on American English press reportage.* Copenhagen: University of Copenhagen.