DEVELOPMENT OF A DIGRAM-BASED TYPING KEY LAYOUT FOR SINGLE-FINGER/STYLUS INPUT

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Hand-held devices often include a keyboard on which a user types with one finger or a stylus. When a user types with one finger, conventional key layouts are not optimal for typing throughput. We used a predictive human performance model based on the frequency of English-language digrams and interkey distances to evaluate alternative key layouts. We also analyzed English digrams with a path-analysis program to determine the strongest links among English letters. The path analysis combined with the predictive human performance model provided a basis for developing and evaluating typing-key layouts for single-finger input. A nonstandard typing-key layout (in a roughly 5 x 5 key matrix) based on digram analysis should, after the development of skilled use, be about 27% better than the QWERTY layout. A nonstandard alphabetic typing-key layout (in a roughly 5 x 5 key matrix) should be about 13% better than the QWERTY layout for single-finger entry.

INTRODUCTION

For hand-held tablet and portable computers (including pen-based systems), it is important to evaluate the best arrangement of keys for typing layouts when users type with one finger or a stylus. Also, improved layouts for one-at-a-time character selection could help the population of computer users whose special needs limit them exclusively to this style of typing.

Several researchers have developed human performance models for skilled typing Card, Moran, and Newell, 1983; Kinkead, 1975; Noel and McDonald, 1989; Rumelhart and Norman, 1982). To evaluate the utility of different typing-key layouts, these models use information about the speed of typing between hands, between fingers on the same hand, and typing letters with the same finger, combined with information about the relative frequency of English-language digrams. These user performance models correspond closely to empirical studies of alternative layouts (Card, Moran, and Newell, 1983; Noel and McDonald, 1989; Norman and Fisher, 1982).

Because a common way to use a small device is to hold it in one hand while typing with the other hand (usually with one finger or a stylus), it is important to develop a typing-key layout that is appropriate for this type of input. The user model for typing with 10 fingers is clearly inappropriate for evaluating layouts for typing with one finger, so the first step must be to develop a user model for one-fingered typing that has a strong empirical basis.

A PREDICTIVE HUMAN PERFORMANCE MODEL FOR ONE-FINGERED TYPING

Fitts' Law (Fitts, 1954; Fitts and Peterson, 1964) is a model of human performance that has an extensive history of empirical validation (Card, Moran, and Newell, 1983). Fitts' Law models the time that a person needs to touch a target accurately, depending on the distance to the target and the size of the target. Specifically, Fitts' Law states:

$MT = a + b\log_2(2A/W)$

where *MT* is the movement time, *A* is the amplitude of the movement (distance to the target), *W* is the size of the target relative to the direction that the person is moving to acquire the target, and *a* and *b* are empirically determined constants. The law essentially states that movement time is constant for any proportional combination of *A* and *W*, and either increasing *A* or decreasing *W* will increase movement time in a specific and definable way.

Clearly, this law should be a fundamental part of a user model of single-finger typing. When someone types with one finger, he or she is performing multiple target (typing key) acquisitions based on the digrams in the text string that he or she is typing. For a typing-key layout, the formula is less complicated because the letter keys are all the same size, so *W* becomes a constant, and now $MT = a + b*\log_2*(2A)$. Therefore, the distance to the target (*A*) is the only variable that affects movement time and, therefore, typing speed (aside from individual differences, which affect only the constants *a* and *b*).

Predictive human performance models for 10-finger keyboards use the frequency matrix of English-language digrams (Card, Moran, and Newell, 1983) and the matrix of empirically derived interkey typing times (Kinkead, 1975) as input. They combine them with the formula: Typing Time = $\mathrm{Sum}(f_i*t_i)$, where *f* refers to elements in the digram-frequency matrix, and *t* refers to elements in the interkey typing-time matrix.

To evaluate alternative one-finger layouts, an appropriate formula is: Typing Time = $FL(\Sigma(f_i*\log2(2d_i)))$, where *f* refers to elements in the digram-frequency matrix, *d* refers to elements in an interkey-distance matrix, and *FL* means "a linear function of." For example, in the QWERTY layout, the distance from "A" to "J" is 6; in the alphabetic layout, it is 9; and for the Dvorak layout, it is 2 (see Figure 1). As defined above, $\log2(2d_i)$ corresponds to time as a function of distance, so $\Sigma(f_i*\log2(2d_i))$ is a measure related to typing speed (in unspecified units), with lower values indicative of faster typing.

QWERTY Layout

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Q W E R T Y U I O P
  A S D F G H J K L
   Z X C V B N M
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Dvorak Layout

```
        P Y F G C R L
   A O E U I D H T N S
    Z Q J K X B M W V
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Conventional Alphabetic Layout

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A B C D E F G H I J
  K L M N O P Q R S
   T U V W X Y Z
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Figure 1. QWERTY, Alphabetic, and Dvorak Standard Key Layouts

There is not much point in trying to develop a more precise estimate of interkey distance. In any given keyboard, the actual size of the keyboard and the shape of the keys may vary according to the limits of the design space. However, the number of keys that a user must cross to get from one letter to another should correlate very highly with other distance measures, and should therefore provide a statistically reliable correlate of distance.

The predictive human performance model returns a value of 2318 for the QWERTY layout, 2389 for the alphabetic layout (3% poorer than QWERTY), and 2777 for the Dvorak layout (20% poorer than QWERTY). The comparison of QWERTY versus alphabetic for single-finger typing is consistent with the finding that novice single- and double-finger typists typed faster with a QWERTY than with an alphabetic layout (Francas, Brown, and Goodman, 1983).

Dvorak sought to separate the most frequent English-language digrams to take advantage of the fact that alternating hand sequences are the fastest for 10-fingered typing (Norman and Fisher, 1982). The comparison of QWERTY versus Dvorak is consistent with the reasoning that the strength of the Dvorak layout for 10-fingered typing makes it the weakest for single-fingered typing.

A NETWORK MODEL OF ENGLISH-LANGUAGE DIGRAMS

To improve the layout for single-fingered typing, it is reasonable to analyze the English-language digrams to determine the relative associative strengths among the letters so the layout can minimize the distance between strongly associated letters. To do this, we first created a symmetrical matrix of the relative frequency of unordered English-language digrams (to two significant digits) by summing corresponding cells of the ordered digrams (using tables presented in Card, Moran, and Newell, 1983). We analyzed this matrix with the Pathfinder network-definition program (Cooke and McDonald, 1987; Schvaneveldt, Durso, and Dearholt, 1985), setting the key parameters of *r* (the Minkowski *r*-metric) to infinity and *q* (the maximum number of links in a path) to *n*-1. These settings create a minimally connected network, and are the settings that most researchers who use Pathfinder prefer (Cooke and McDonald, 1987). Table 1 shows the results of the Pathfinder network analysis of English-language digrams. Figure 2 shows the results as a graph.

Table 1. Pathfinder Network Analysis of English-Language Digrams

Link Number	Node 1	Node 2	Weight
1	H	T	2
2	E	H	7
3	I	N	11
4	A	N	14
5	E	N	16
6	I	T	16
7	E	S	17
8	N	O	18
9	O	R	18
10	D	E	19
11	A	L	25

Table 1. Pathfinder Network Analysis of English-Language Digrams (cont.)

Link Number	Node 1	Node 2	Weight
12	F	O	25
13	O	U	25
14	G	N	26
15	E	V	26
16	E	M	27
17	A	C	28
18	B	L	30
19	O	W	31
20	E	W	31
21	A	W	31
22	O	P	33
23	L	Y	33
24	J	L	33
25	E	P	33
26	A	P	33
27	L	Q	35
28	E	K	35
29	E	X	36
30	E	Z	37
31	I	Z	37

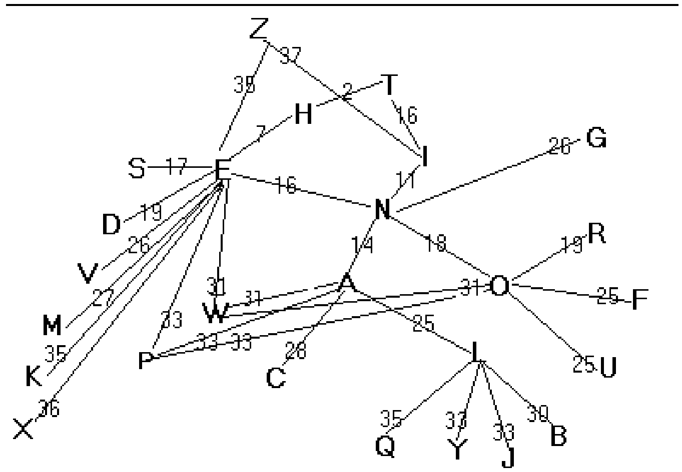

Figure 2. Graph of English-Language Digrams

Note: The link length is represented by numbers on the lines, not by line length. Larger numbers indicate a greater distance (weaker association) between nodes.

A NEW LAYOUT BASED ON THE NETWORK ANALYSIS

The primary design goal that relates to the network analysis is to minimize the distance between letters that are closely connected. A related goal is to place letters that connect to many other letters in the center of the matrix of letter keys. The most closely connected digrams were "TH," "HE," "IN," "AN," "EN," and "IT." The letters with the most connections to other letters were "E" (with 11), "O" (with 6), "N" (with 5), "A" (with 5), and "L" (with 5).

The conventional rectangular arrangement of typing keys (roughly 3 x 10 keys, short and wide) supports typing with 10 fingers, but is not optimal for typing with one finger because the maximum possible distance between keys is 9 keys. An arrangement that minimizes the maximum interkey distance is a matrix that is roughly 5 x 5 keys. Figure 3 shows a digram-based layout consistent with these constraints. The predictive human performance model returned a value of 1699 for this arrangement, 27% better than QWERTY. Figure 3 also shows an alphabetic layout designed to minimize the maximum interkey distance (with a predictive value of 2006, 13% better than QWERTY).

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       Digram            Alphabetic

  Q R W X Y            A B C D E
  L U A O F            F G H I J
Z T H E N G            K L M N O
  V D I S P            P Q R S T
  B C M J K            U V W X Y Z
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Figure 3. Two New Key Layouts

DISCUSSION

The analyses in this study used a predictive human performance model rather than user testing for evaluation. However, this is a common approach for this type of problem as long as a reasonable user model (such as Fitts' Law) exists. As Norman and Fisher(1982) put it in their influential paper on the evaluation of alphabetic keyboards for 10-fingered typing:

"We despaired of doing the actual experiments because to have done so would have required months of training on a variety of keyboards to get people to expert status, and then a considerable amount of retraining of the subjects so that they were back to normal on regular typewriters." (p. 514)

This analysis clearly judges the digram-based layout to be better than the other layouts. In an application that requires the greatest possible typing throughput (including the user incentive to acquire expert skill), the best choice is the digram-based layout in the roughly 5 x 5 key arrangement. Sears (1991) reported that users type about 20 words per minute (wpm) on a touchscreen keyboard (with a QWERTY layout) that is only 70 mm wide. By changing the layout from QWERTY to the new digram-based layout, this average could improve to about 25 wpm. Sears (1991) also reported that if touchscreen keys are 22.7 mm square, then users type about 25 wpm (with a QWERTY layout). Again, with the new digram-based layout, this average could improve to about 32 wpm.

Although the digram-based layout may provide the best typing throughput, it would require some practice to achieve an effective skill level. However, if the application requires the maximum possible typing throughput, the user will probably do extensive typing with the layout and, according to the power law of practice (Card, Moran, and Newell, 1983), should rapidly learn and become proficient with the layout.

If the application does not require the maximum possible typing throughput, then the alphabetic layout in the roughly 5 x 5 key arrangement may be a better nonconventional layout. In this case, the user probably will not type enough for the power law of practice to apply, and it will be more important to provide a letter arrangement that matches the user's knowledge of the alphabet. In previous settings, human factors engineers have warned against the use of alphabetic layouts because they are less effective than QWERTY in a conventional arrangement. However, if users type 20 wpm with a QWERTY layout, then they should be able to type about 23 wpm with this improved alphabetic arrangement (given sufficient practice). If they type 25 wpm with a QWERTY layout, then they should be able to type about 28 wpm with the improved alphabetic arrangement.

The approach used to create this layout is similar to the approach used by Soukoreff and MacKenzie (1995) to determine the theoretical upper bound of stylus typing on a standard soft keyboard. Note that this approach does not guarantee that the layout is optimal with respect to the performance model, but it is likely to be close to optimal and might be somewhat easier to use initially than a layout produced by completely automated means (Lewis, LaLomia, and Kennedy, 1999).

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