USING SEQUENTIAL DATA ANALYSES TO DETERMINE THE OPTIMUM LAYOUT FOR AN ALTERNATIVE KEYBOARD

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The standard QWERTY keyboard was developed over a hundred years ago. It is suspected to be involved in repetitive strain injuries, such as carpal tunnel syndrome (CTS). To reduce and eliminate many of the movements that are suspected to contribute to CTS, a new type of alphanumeric input based on the chording concept was designed. This AID-CTS keyboard is an alphanumeric input system that uses a pair of devices each comprised of an inverted dome upon which the hands rest. As a chordal device, the AID-CTS keyboard typing methodology entails creating a keystroke via a combination of positions of the two domes. The purpose of the current study was to determine a new character layout that would reduce the ergonomic impact of typing further. Two studies were conducted. In Study 1, we analyzed two-letter sequences using sequential, multi-way frequency analyses and established a listing of the most important two-letter transitions. In Study 2, we created a number of competing character layouts and analyzed them regarding their ergonomic impact. The studies resulted in an optimum layout that minimizes arm and wrist movements.

INTRODUCTION

The de-facto standard QWERTY keyboard layout was developed over a hundred years ago and has not changed since then. Additionally, the QWERTY keyboard has become suspect in causing repetitive strain injuries (RSIs), such as carpal tunnel syndrome (CTS).

To reduce and eliminate many of the movements that are suspected in the development of CTS, a new type of alphanumeric input based on the chording concept was designed (McAlindon, 1995; 1997). This AID-CTS keyboard (a.k.a. OrbiTouch by Keybowl, Inc.), as depicted in Figure 1, is an alphanumeric input system that uses a pair of inverted domes upon which the hands rest. Each dome is flexibly coupled to a base. The design alleviates many of the problems of key spacing, key size, and key force that are part of every traditional QWERTY type keyboard.

AID-CTS keyboard users are expected to be the ones that (a) have an upper extremity disability, (b) suffer from CTS, or (c) are worried about CTS risk as it relates to typing and are willing to consider a keyboard alternative. Different attachments can be used in place of the dome (e.g., ball, flat board, or joystick). Other features of the AID-CTS keyboard include adjustable dome movement force and displacement, as well as adjustable tilt and height.

As a chordal device, the AID-CTS keyboard typing methodology entails creating a keystroke via a combination of positions of the two domes. Referring to Figure 2, moving the left dome in the direction of the white arrow and the right dome in the direction of the black arrow types the corresponding character. A capital letter is created using the same two motions with one exception: press and hold the left dome down. Each dome moves in a compass rose arrangement: N, S, E, W, NE, SE, NW, SW. The order in which the domes are moved to their respective locations does not matter, nor does the timing between the two domes.

Figure 1: The AID-CTS keyboard for use by individuals with upper extremity disability.

Figure 2: Two inputs, one from each hand, are required to type a character.

Purpose of the Current Studies

In previous research (e.g., McAlindon & Jentsch, 1999), we were able to demonstrate significant reductions in ergonomic impact with an AID-CTS design that used a character layout mapped so that the required hand motions were equivalent in direction to the QWERTY-keyboard. The purpose of the current studies was to determine a new character layout which would reduce the ergonomic impact further, while maximizing typing comfort.

STUDY 1: IDENTIFYING IMPORTANT TWO-LETTER SEQUENCES

Background

In Study 1, we wanted to extend existing work (e.g., Dvorak, Merrick, Dealey, & Ford, 1936; Shieh & Lin, 1999) and identify those two-letter sequences (digrams) that are most important for keyboard designers. While traditional frequency data on two-letter sequences are helpful, they do not readily provide critical information regarding the relative likelihood of sequences beginning with the same letter (e.g., HE vs. HA) or ending in the same letter (e.g., TH vs. PH). Multi-way frequency analysis of sequential text data, however, provides “value added.” The statistical likelihood of each digram is given in the form of a z-score which describes whether it occurs significantly more or less often than one would expect by chance alone. Thus, not only does the researcher end up knowing that a digram occurs frequently, but also whether its occurrence is statistically significant.

STUDY 1: METHOD

Text samples

We used ten different electronic text samples, each 45,056 characters long. Two were current event articles from the Cable News Network (CNN) web site. One was an electronic file of business letters. Segments of two different chapters in aviation psychology, a software specification, and an article on cancer cells from an on-line medical journal were also analyzed. Finally, we used electronic copies of “Robinson Crusoe” by Dafoe (2 samples), and one of the English version of Verne’s “Around the World in 80 days.”

Character coding

In all text samples, the two-character transitions were categorized using a 29-item coding system. Any numeral (i.e., 0 through 9) was coded as "1." The letters A through Z [whether capitalized or not] were coded as "101" through "126." Spaces were coded as "130," and all other punctuation marks were coded as "131".

STUDY 1: RESULTS

Analysis Strategy

The two-letter digram transitions were analyzed using SPSS Windows 7.5 General Loglinear, creating fully saturated models of the structure: Constant + Letter1 + Letter2 + Letter1 * Letter2. Given this 30 x 30 matrix (including a constant and the single letters), 900 parameters resulted. Since, in each sample, 45,056 transitions were analyzed, we obtained a ratio of observations to matrix elements of 50:1.

Analysis of Significant Digrams

The loglinear models provided parameter estimates for each digram transition. A significant positive/negative z-score for a parameter estimate indicated that a digram occurred significantly more/less often than expected by chance alone.

The z-score criterion was set at a conservative level of $z_{crit} = 3.30$, $p < .001$ (two-tailed). Thus, we would have expected one or two of the 900 transitions to be significant by chance alone. As is indicated in Table 1, however, many more significant parameter estimates were found. In fact, a chi-square test of the observed vs. expected significant transitions in the samples showed that, in each case, significantly more transitions were statistically significant than one would have expected by chance alone.

The parameter estimates from the current study were compared to the frequency data by Shieh and Lin (1999), and several interesting differences were noted. For example, while the frequency data showed “TH” to be by far the most frequent digram (20662 in Shieh & Lin), it was not more likely according to our analysis than the much less frequent sequence “IC” (3790 in Shieh & Lin). The reason was that there are many common transitions beginning with “T” or ending with “H” (not all resulting in “TH”), but very few that begin either with “I” or end with “C.” Thus, there was added value for the researcher who needs to know where to place the “I” in relation to the “C.”

STUDY 2: ANALYSIS OF THE ERGONOMIC IMPACT OF DIFFERENT CHARACTER LAYOUTS

Background

Using the data from Study 1, the purpose of Study 2 was to develop and test a number of alternative character layouts which would minimize the required movements for the chording of the AID-CTS keyboard. Based on previous studies, certain movements could be identified a priori as having a higher difficulty and ergonomic impact than others. Combining this information with the results from Study 1, a merit value could be calculated for each keyboard layout and compared.

STUDY 2: METHOD

Character Layouts

Overall, 51 different layouts were tested. Five layouts were created by assigning letters in accordance with systematic sequences, such as alphabetical order, single-letter frequency, or digram occurrence. For example, the layout “Alphabetical, left hand fixed, right hand moving” was created by assigning the first eight letters of the alphabet (i.e., “A” through “H”) to the left dome position North (i.e., Left-North). “A” was then assigned to Right-North, “B” to Right-Northeast, etc. The next eight letters (i.e., “I” through “P”) were assigned to Left-Northeast, and to Right-North through Right-Northwest (NW) positions. In a similar manner, the following layouts were created:

1. Alphabetical, left hand fixed, right hand moving.
2. Alphabetical, left hand moving, right hand fixed.
3. By single-letter frequency, optimized for digrams, alternative A.
4. By single-letter frequency, optimized for digrams, alternative B.
5. By single-letter frequency, using the 1, 5, 3, 7 positions first and avoiding 90 degree transitions. Five other layouts were created by mapping existing keyboards onto the spatial layout of the AID-CTS:
6. Equivalent of the "As-In-Red-Hot" layout.
7. Equivalent of the "Choate" layout.
8. Equivalent of the "Chubon" layout.
9. Equivalent of the "QWERTY" layout
10. Equivalent of the "QWERTY" layout, but optimized by single-letter frequency.

The remaining 41 layouts were created by an Excel macro that randomly assigned letters to the AID-CTS keyboard alternative.

Impact Algorithm

From previous research (McAlindon, Stanney, & Silver, 1995), we knew that the character positions with the highest ergonomic impact and the most errors were the NW, SW, SE, and NE positions. Additionally, all movements requiring a transition of 90 degrees on either hand (e.g., from N to W) were difficult and had high ergonomic impact.

Impact scores. A program was written in Microsoft Access '97 to model these relationships. The algorithm assigned the following impact values:

1. Unweighted model: Regardless of the direction of the movement, an impact value of "1" was assigned for any movement requiring a position change (e.g., N – S, or N – W). An impact value of "0" was assigned for any movement not requiring a position change (e.g., N – N).

2. Weighted model: In the weighted model, the movements for each hand were weighted based on previous research. A value of "3" (high) was assigned for all 90-degree movements into the difficult NW, SW, SE, and NE positions. A "2" was assigned for 90-degree movements into the W, S, E, and N positions. Finally, a "1" was assigned for all other movements requiring a position change; whereas "0" was assigned for a movement that did not require a position change.

Overall impact scores for each layout. Once the impact scores for each two-letter transition and each layout were calculated, the computer calculated the overall impact score for each layout. The weighted and unweighted scores were multiplied by the z-scores for two-letter transitions calculated from Study 1 and then summed. This provided an estimate of the impact using sequential data analysis. The weighted and unweighted scores were also multiplied by the relative frequencies for two-letter transitions from Shieh and Lin (1999) to get an additional estimate of ergonomic impact.

Comparisons across layouts. The impact scores of each layout were (a) ranked and (b) transformed into a percentage of the score attained by the QWERTY-mapped equivalent. This provided an estimate of relative merit of each layout. Based on the overall average percentage and the overall average rank, an overall rank of impact (1 = lowest to 52 = highest) was calculated.

STUDY 2: RESULTS

The results of the analyses are shown in Table 2. There was a wide range of impact scores among the ten structured layouts. Furthermore, random layouts (not shown in Table 2) were substantially worse than the optimized layout, and did randomly fall around the QWERTY-mapped equivalent.

Table 2
Results of the Impact Analysis.

Description	Average Percent[1]	Average Rank[2]
By single-letter frequency, using the left-hand 1, 2, and 8 positions first, right hand 1-8, optimized for digram transitions	82	1
By single-letter frequency, using the left-hand 1, 2, and 8 positions first, right hand 1-8	86	2
Alphabetical, left hand fixed, right hand moving	93	4
Choate-mapped equivalent	94	4
As-In-Red-Hot-mapped equivalent	95	5
Alphabetical, left hand moving, right hand fixed	98	6
QWERTY-mapped equivalent	100	7
Chubon-mapped equivalent	103	8
QWERTY-mapped equivalent, optimized by letter-frequency	104	9
By single-letter frequency, using the 1, 5, 3, 7 positions first and avoiding 90 degree transitions	105	10

Notes: [1] Aver Perc = Average percentage of impact, as compared to the QWERTY-mapped equivalent ($P_{QWERTY\text{-}Equivalent}$ = 100), across the five analyses
[2] Aver Rank = Average rank of impact, across the five analyses

The best layout was the "By single-letter frequency, using the 1, 2, and 8 Positions first, and optimized for digrams", with an average impact rank of 1 and an average impact percentage of 82 (as compared to the QWERTY-mapped equivalent).

DISCUSSION

The two studies described above aided in determining the most appropriate layout for a new alphanumeric input device (the AID-CTS keyboard) that is based on left- and right-hand gross motor movements versus the standard nine fine motor movements of the fingers in typing with the QWERTY keyboard. As such, the studies provided insight into how to best reconcile speed tradeoffs in gross vs. fine motor skill requirements in typing with the AID-CTS keyboard. The analyses of character frequency and sequences from varied writing examples allowed for the construction of an AID-CTS character arrangement that is best suited to maximize typing speed as well as to maximize comfort in using the AID-CTS keyboard.

Table 3
Optimized Layout vs. QWERTY-mapped Equivalent Layout.

Letter	Optimum L	Optimum R	QWERTY L	QWERTY R
A	NE	NE	SW	W
B	NW	NE	SE	SE
C	NE	E	S	SE
D	NE	NW	NE	E
E	N	N	N	N
F	NE	SE	S	E
G	NW	E	SW	E
H	N	SW	NW	W
I	N	S	N	NW
J	NW	SE	N	W
K	NW	S	NE	W
L	NE	N	SE	W
M	NE	S	S	SW
N	N	NW	SW	SW
O	N	E	NE	N
P	NE	SW	E	N
Q	E	N	W	NW
R	N	W	N	NE
S	N	SE	S	W
T	N	NE	NE	NE
U	NE	W	NW	NW
V	NW	W	SW	SE
W	NW	NW	NW	N
X	NW	SW	SW	S
Y	NW	N	NE	NW
Z	E	NE	SE	SW
SPC	E	E	E	E

Notes: Optimum = Optimum Layout; QWERTY = QWERTY-mapped equivalent
L = Left-Hand Dome= Right-Hand Dome
Positions: North, Northeast, East, Southeast, South, Southwest, West, Northwest.

Use of multi-way frequency analyses of two-letter sequences resulted in data that augment existing data on the relative frequencies of digrams in English text. These analyses helped establish which characters would be placed in which positions around the AID-CTS domes to help minimize those motions (and thereby increase speed) required in typing common transitions. Comfort was also considered as one of the main factors and was addressed through the assignment of characters to the easiest positions to actuate on the AID-CTS domes.

Second, an optimized layout was created from an impact standpoint that is different from the QWERTY-mapped equivalent and other, alternative layouts. This layout, shown in Table 3, reduces movements significantly (especially the difficult ones), and it clusters the letters in the NW, N, and NE positions on the left hand (the non-dominant hand for right-handed individuals), while using all positions in the dominant (right) hand. This optimized layout is to provide the AID-CTS keyboard typist with the fastest means of typing without compromise to comfort.

With the analyses of the digrams and single character letter frequencies complete at this initial stage, several future studies can be conducted to help determine which character layout for the AID-CTS keyboard would be most appropriate for the common trigram combinations. Other future studies could include using all of the characters on a standard keyboard. The model that was constructed to perform our initial analyses could be easily expanded to include all of the characters, numerics, and special function keys of a regular keyboard.

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