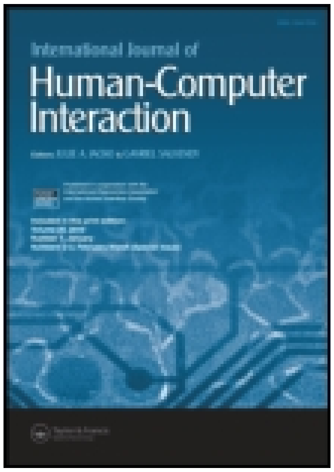

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Chinese Keyboard Layout Design Based on Polyphone Disambiguation and a Genetic Algorithm

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This study suggests a new keyboard layout to efficiently type in Chinese characters. The layout was based on a statistical analysis of Chinese corpus and was derived from a genetic algorithm. In the semantic analysis, 6 million Chinese characters were transcribed into typing script. Macros of polyphone were disambiguated from either the context or the presence probabilities in the training data. Relative frequencies of single letter and letter pair were counted to investigate on tapping workload and sequence. In the genetic algorithm, five ergonomics criteria—tapping workload distribution, hand alternation, finger alternation, avoidance of big steps, and hit direction—were applied to evaluate keyboard layout alternatives. The result showed that the proposed layout is 43% better than the QWERTY layout in terms of the weighted sum of the five ergonomic criteria.

1. INTRODUCTION

Since the traditional QWERTY layout appeared on the typewriter in 1878, many efforts have been made to improve its inherent inefficiency (Dvorak, 1943; Griffith, 1949; Noyes, 1998; Sanders & McCormick, 1993). As one of several alternative layouts, the Dvorak Simplified Keyboard (DSK) has been very positively evaluated in terms of user performance and learnability (Seibel, 1972; U.S. Patent No. 2,040,248, 1936). The DSK layout, however, can be very inefficient when typing in languages other than English, because it was designed using only the English corpus. This fact is also true for some languages of Latin origin such as Spanish, French, Portuguese, and German. As such, each language needs its own research to design an optimal keyboard layout. Significant research has examined the keyboard layout design, but research with languages of non-Latin origin such as Chinese is relatively rare. With its many polyphones, analyzing the Chinese corpus is more difficult. Thus, a complicated semantic analysis is necessary to develop an optimal design of Chinese keyboard layout.

The Chinese do not use the English alphabet system but use characters called "Hanzi." "Pinyin" is the official system used to transcribe Chinese characters into Latin script (Taylor & Taylor, 1995). This system is widely used for computer typing. It has been shown that more than 97% of Chinese computer users use the Pinyin input method editor (IME). Considering that Chinese speakers (about 20%) and English speakers (19%) constitute the largest populations in the world (Internet World Stats, 2012), the optimal layout design of the Chinese keyboard is regarded as very important in computer-related industries. In addition, the advent of type for mobile devices such as smartphones and tablet PCs is anticipated to increase the worth of an optimal keyboard layout design for China.

The contribution of this article is threefold. First, important linguistic statistics of Chinese were provided with the consideration of polyphone characters. Single-letter frequencies and letter-pair frequencies were calculated and presented. This was done on a Chinese corpus having 6 million characters. The process to disambiguate polyphones was deliberately designed so that all polyphones could be converted into typing script according to their context or the presence probability dictionary. Second, an optimal Chinese keyboard layout was derived from the linguistic statistics calculated previously, with a focus on typing performance based on ergonomic criteria. Dimensionless ergonomic criteria and a genetic algorithm were used for the evaluation of countless random layouts. As a result, the new layout gained 43% improvement based on the weighted sum of the ergonomic criteria over the QWERTY layout. Third, the procedure of optimizing a keyboard layout was introduced in details (in sections 3 and 4) so that researchers who are interested in keyboard layout designs for any language can easily follow and implement.

2. RELATED WORK IN KEYBOARD LAYOUT DESIGN

An improperly designed computer keyboard can result in poor efficiency and serious damage to the wrist (Armstrong, Castelli, Evans, & Diaz-Perez, 1984; Armstrong, Fine, Goldstein, Lifshitz, & Silverstein, 1987; Armstrong & Chaffin, 1979; Silverstein, Fine, & Armstrong, 1987), whereas a good design should have four objectives: (a) reduce typing fatigue, (b) enhance input speed, (c) minimize errors, and (d) facilitate quick learning (Zhai, Hunter, & Smith, 2000). A balance should

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be achieved, however, among these four objectives because of their inner correlations. For example, it was found that typing errors are due in part to the typist's mental and physical state and are often associated with fatigue and a higher typing rate (Hiraga, Ono, & Hisao, 1980). Thus as optimizing typing rate is the main objective, reducing typing errors should also be taken into consideration.

2.1. Research Directions in Keyboard Design

To date, keyboard design has been improved mainly in two directions—physical change and layout adjustments.

Physical change is one approach to making an ergonomic keyboard by improving the user's posture against the keyboard. Representative solutions in this category include splitting the keyboard (U.S. Patent No. 1,138,474, 1915), which was evaluated to improve comfort and prevent pain in keyboard users (Kroemer, 1972; Marek, Noworol, Wos, Karwowski, & Hamiga, 1992; Nakaseko, Grandjean, Hüunting, & Gierer, 1985; Rolf, 1987). Space restrictions of some keyboards, however, such as the small area on a laptop computer, have impeded promoting this design.

Layout adjustment is another approach to improve efficiency and user satisfaction by designing new keyboard layouts based on statistical data and human factors principles. One typical work in this category is the DSK layout (U.S. Patent No. 2,040,248, 1936), which was designed to assign workloads proportional to finger strengths, increase the use of a home row, and motivate typing with two hands. This work was followed by Biegel (1934), Griffith (1949), and Ward (1936). New keyboard layouts have been demonstrated to yield a better keying rate (Noyes, 1983; Stewart, 1973). In contrast to physical change, layout adjustments deal with the nature of the design problem. Because adjusting the layout offers more cost savings and is easier to implement, it was used in this study.

2.2. Evaluating the Keyboard Layout and the Search Algorithms

Many ergonomists have studied the mathematical modeling of the keyboard layout problem. To calculate total typing time, the first model multiplied frequencies of letter pairs with their travel time. Hiraga et al. (1980) conducted a study to express the time intervals between keystrokes as a function of relative key locations, word frequency, and other factors such as probability fluctuations and the context of text. Along with other models (Fitts, 1954; MacKenzie, 1989; Rosen, Goodenough-Trepagnier, Getschow, & Felts, 1986; Welford, 1968), an optimization based on this model focused only on typing speed without considering some essential ergonomic criteria such as alternative hand use and finger load distribution (Li, Chen, & Goonetilleke, 2006). Without considerations of these ergonomic criteria, it cannot be assured that keystrokes with higher tapping workload are assigned to stronger fingers. Marsan (French Patent 2,446,723, 1976; French Patent 2,611,589, 1987) proposed an improved model by quantifying a set of six human factors criteria and summing up all the variances between the given layout and an ideal layout as penalty points. Later researchers also adopted this model (Eggers, Feillet, Kehl, Wagner, & Yannou, 2003; Wagner, Yannou, Kehl, Feillet, & Eggers, 2003) and yielded an English layout 41% better than the QWERTY layout, a French layout 51% better than the AZERTY layout, and a German layout 41% better than the QWERTZ layout.

The simple idea to determine an optimal layout is to compare all candidate layouts with one another and choose the best one. Thus, an entire search of all possible layouts is necessary. If no heuristic algorithm is applied, however, this search may require billions of years using a powerful computer. The simulated annealing algorithm was first applied in solving the keyboard layout problem (Light & Anderson, 1993). This was followed by a genetic algorithm with two pooled approach to reduce the necessary computation time (Walker, 2003). Recently, many researchers have favored a genetic algorithm based on the ant colony optimization in designing keyboard layouts for the English, French, German, and Hindi languages (Deshwal & Deb, 2003; Eggers et al., 2003; Goettl, Brugh, & Julstrom, 2005; Malas, Taifour, & Abandah, 2008; Wagner et al., 2003).

Table 1 lists the evaluation functions, algorithms, and targeted languages of previous research. In the present study, the genetic algorithm based on Marsan's (French Patent 2,611,589, 1987) six ergonomic criteria was applied to find the optimal keyboard layout based on statistics generated from the Chinese corpus.

2.3. Previous Research on Chinese Linguistic Statistics

Zhang and Guan (2006) were the first to investigate the statistics of Chinese corpus, and their research covered 5 million Chinese characters including politics, science, and literature topics. The characters were turned into typing script under the Pinyin IME, and the frequencies of 26 Latin letters were counted. The result could not be used directly for keyboard research, however, for two reasons. First, 15% or more of Chinese characters are polyphones as calculated in section 3 of this study. Ignoring polyphone disambiguation in transcribing Chinese characters into typing script could result in inaccurate letter statistics. Second, only single-letter frequencies were provided. In keyboard design, letter-pair frequencies could be more important, because the letter pair is often the unit used to describe typing behavior, and it is used in the mathematical model.

3. LINGUISTIC STATISTICS OF CHINESE CORPUS

A computer program was developed for the present study to calculate Chinese linguistic statistics. Relative frequencies of a single letter and letter pairs were obtained as the basic information for the optimal design of Chinese keyboard layout. Table 2 presents the definition of some important terms. Note that a polyphone character defined in this study, as a character that has at least two different macros, differed from

TABLE 1
Evaluation Function, Algorithm and Targeted Language of Previous Researches

Research	Evaluation Function	Algorithm	Targeted Language
Light and Anderson, 1993	Relative frequency of Letter Pair × Travel Time	Simulated annealing	English
Walker, 2003	Penalty points awarded to specific letter pairs	Genetic with two pooled approach	English
Eggers et al., 2003	Six Marsan's ergonomic criteria	Ant Colony optimization	French, German, English
Wagner et al., 2003	Six Marsan's ergonomic criteria	Ant Colony optimization	French, German, English
Deshwal and Deb, 2003	Six Marsan's ergonomic criteria	Genetic	Hindi
Goettl et al., 2005	Four Marsan's ergonomic criteria	Genetic	English
Malas et al., 2008	Relative frequency of Letter Pair × Travel Time	Genetic	Arabic

TABLE 2
Definition of Important Terms in Calculating Chinese Linguistic Statistics

Term	Definition
Character	A character is the smallest unit in a Chinese text. For example, "汉字" are two Chinese characters, and either "汉" or "字" is a single character.
Pinyin	A Pinyin is a Chinese phonetic alphabet. For example, the Pinyin of "汉" is "hàn" whereas the Pinyin of "字" is "zì".
Macro	A macro is a Pinyin without the tone indicator. It is also the typing script if one uses the Pinyin input method editor. For example, the macro of "汉" is "han" whereas the macro of "字" is "zi".
Letter	A letter is the smallest unit in a macro, and it exactly maps a key in the keyboard for Chinese input. For example, there are three letters in the macro of "汉" which are h, a, and n, whereas two letters exist in the macro of "字" (z and i).
Letter pair	A letter pair is a pair of two consecutive letters. For example, the combination of z and i is a letter pair in the macro of "字".
Polyphone	In this study, a polyphone is referred to a Chinese character that has at least two different macros.

the definition in a Chinese dictionary (a character that has at least two different Pinyins). The reason to change this was that when a Chinese character was typed, the tone indicator was not necessary.

3.1. Data Processing

Training and testing data. The algorithm to calculate Chinese linguistic statistics needed to develop the dictionary first, because the polyphone's typing script was identified either from the context or from the presence probability dictionary, which did not previously exist. Thus, training data were used to generate the polyphone macro probability dictionary (PMPD), and testing data were used to run the program. Both data sets were selected randomly from a wide collection of articles that covered scientific, political, and literary content. These articles were retrieved from a Chinese document-sharing platform in May 2010. Spaces in the text were removed because they were not considered in the design. Three thousand characters were used for the training data, and 6 million characters were chosen for the testing data, as shown in Table 3.

TABLE 3
Sample Sizes of the Training and Testing Data

Category	No. of Characters in the Population	Sample Size of the Training Data	Sample Size of the Testing Data
Science	4,247,261	10,000	2,000,000
Politics	7,011,469	10,000	2,000,000
Literature	5,387,486	10,000	2,000,000
Total	16,646,216	30,000	6,000,000

The result of analyzing the training data was summarized into the PMPD, and its structure is given in Table 4. If the polyphone failed to achieve disambiguation from the context, it could be assigned a macro proportional to the presence probability distribution. Note that no Chinese characters have more than three different macros.

TABLE 4
Structure and Examples of the Polyphone Macro Probability Dictionary

Character	Macro 1	Macro 2	Macro 3	Probability of Macro 1	Cum. Probability of Macro 1 and 2	Cum. Probability of 1, 2, and 3
差	cha	chai	ci	0.67	0.83	1.00
角	jiao	jue		0.40	1.00	1.00
. . .						

Note. A random number between 0 and 1 is used to assign the polyphone with a macro proportionally to its presence probability distribution in the training data.

Procedures of data processing. All characters in the testing data were transcribed into macros on a one-by-one basis. As shown in Figure 1, monophones and polyphones were identified with a check in the polyphone macro dictionary (PMD) and were treated differently. The PMD stored polyphones, macros, and their usual phrases. The structure of the PMD and examples are shown in Table 5.

Monophones were given macros from the monophone macro dictionary (MMD), which was established from the standardized Chinese character set (GB2312-80). Polyphones obtained macros in a more complicated way, where the semantic and probability-based algorithm was applied. Specifically, the polyphone was returned to its context and combined with one preceding and one following character into two words. These two words were then looked up in the PMD. If only one of them was found in the PMD, the macro of the polyphone was set; if none or both words were found, the PMPD was used to determine a macro for the polyphone.

For example, "称" in "对称图形" was identified as a polyphone. Therefore, "对称" and "称图" were developed from the original context, followed by a search in the PMD. Because only "对称" was found in the PMD, "称" was marked with the macro "chen." Sometimes neither or both words were found in the PMD. If this happened, a random number between 0 and 1 was generated and used by the PMPD to determine the macro for the polyphone. For example, "差" was a polyphone, but the two words developed from the original context with it could not be found in the PMD. A random number between 0 and 1 was generated for this case. If the random number was less than 0.67, then "差" was assigned with macro 1 (cha); if the random number was between 0.67 and 0.83, then "差" was assigned with macro 2 (chai); otherwise, it was assigned with macro 3 (ci). Hence, the semantic and probability-based disambiguation process was used to assign every character with a determined macro.

After every character was set with the macro, the final step of the statistical data processing was to count the frequencies of a single letter, letter pairs, and initial letters. Relative frequencies of a single letter and letter pairs were used later as basic data to design the Chinese optimal keyboard layout.

3.2. Statistical Results

Relative frequencies of a single letter and letter pairs. As shown in Table 6, relative frequencies of a single letter were computed and sorted in descending order. "I", as identified by the calculation, was the most frequent letter used when typing the Pinyin IME. It was not surprising that all vowels ("A", "E", "I", "O", and "U") were also among the most frequently used letters in the Pinyin system. In addition, three other characters among the top eight most-frequent letters—"N", "H", and "G"—are also easily understood because many Chinese words begin or end with these letters. For example, "N" and "G" have higher frequencies than other consonant letters, because they always appear in finals (e.g., an, ian, uan, van, en, in, uen, vn, ang, iang, uang, eng, ing, ueng, ong, iong). The letter "H" is also frequently used in initials (e.g., zh, ch, sh).

The relative frequencies of letter pairs are shown in Table 7, where the first column in the table represents the first letter in the letter pair and the first row represents the second letter in the letter pair. Notably, the matrix was asymmetric due to letter pair sequence. The most frequent pair proved to be N, followed by G, which is also due to their high occurrence in the finals.

Other frequency results. Initial letter frequencies in each macro are shown in Table 8. This could be helpful in other research in designing the Chinese chord keyboard, where it has been suggested that frequent letters be assigned to different keys to reduce the input ambiguity of a Pinyin sequence (Dell'Amico, Diaz, Iori, & Montanari, 2009). Further noticeable is that Chinese Pinyins do not start with U, V, or I, where the frequencies were zero.

4. MODELING THE KEYBOARD LAYOUT PROBLEM

Three steps were taken to design the optimal keyboard layout using the linguistic statistics. First, the keyboard layout problem was simplified and was then represented in a mathematical model. Second, ergonomic guidelines were quantified into evaluation criteria and a weighted penalty formula was developed. Third, a genetic algorithm was applied to the problem to arrive at a final result.

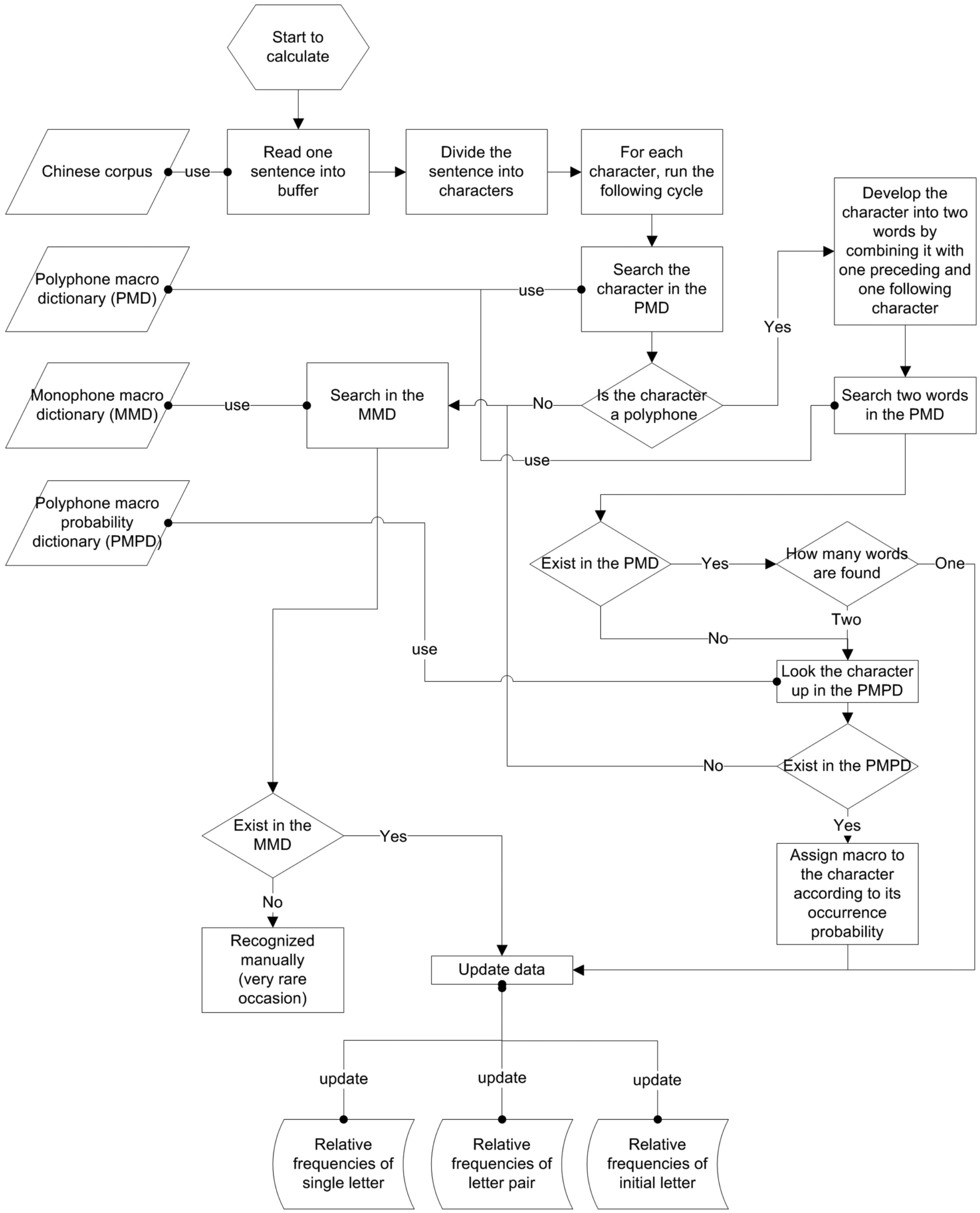

FIG. 1. Process chart to calculate Chinese linguistic statistics. *Note.* Every character is given a determined macro through this process. Polyphones are disambiguated with the context or according to the presence probability in the training data.

4.1. Description to the Keyboard Layout Problem

The Chinese Pinyin IME does not use function keys such as Shift, Ctrl, or Alt in typing; therefore, only 26 English alphabetic letters were considered in the new design of an optimal layout. Other keys such as the space bar and punctuation keys were also excluded from the present research.

A representation of a keyboard layout is shown in Figure 2, where each keystroke is given a unique array to represent its relative location. The array was constructed with the first element indicating the hand (0 as the left hand, 1 as the right hand), the second element representing the row (0 as the top row, 1 as the home row, 2 as the bottom row), and the third element showing

TABLE 5
Structure and Examples of the Polyphone Macro Dictionary

Character	Macro	Word
差	cha	差错
差	cha	差别
差	chai	出差
. . .		

TABLE 6
Relative Frequencies of a Single Letter

Letter	Relative Frequency	Cum. Relative Frequency
I	13.65%	13.65%
N	11.64%	25.29%
A	10.14%	35.43%
U	7.79%	43.22%
E	7.67%	50.89%
H	7.15%	58.04%
G	6.85%	64.89%
O	5.64%	70.54%
D	3.45%	73.98%
Y	3.21%	77.19%
S	3.19%	80.39%
Z	3.19%	83.57%
J	2.35%	85.92%
L	1.87%	87.79%
X	1.70%	89.48%
C	1.60%	91.08%
B	1.57%	92.65%
M	1.23%	93.88%
W	1.16%	95.04%
T	1.11%	96.15%
R	1.03%	97.19%
Q	0.95%	98.14%
F	0.82%	98.96%
K	0.59%	99.55%
P	0.36%	99.91%
V	0.09%	100.00%

Note. The relative frequencies are in descending order.

the column (0 as the thumb, 1∼5 from inward to outward as the fingers). Note that each index finger is in charge of two columns according to the normal hitting rules. Thus, the keyboard layout problem can be expressed as mapping the key locations to 26 English alphabetic letters.

4.2. Evaluation Function

Among Marsan's six ergonomic criteria (Deshwal & Deb, 2003; Wagner et al., 2003), five criteria—tapping workload distribution, hand alternation, finger alternation, avoiding big steps, and hit direction (except for the number of keystrokes)—were employed to evaluate keyboard layout alternatives in the present study. The remaining criterion in Marsan's six ergonomic criteria, the number of keystrokes, was not considered because it has been used for chord keyboards. For the five indicators, the first used the relative frequency data of a single letter, whereas the other four used the relative frequency data of letter pairs. Then, all criteria were weighted differently and summed to obtain an evaluation score for the keyboard layout. The process of turning each indicator dimensionless was improved from previous studies using the average score of random layouts. The evaluation function was finally employed on the genetic algorithm.

Tapping workload distribution. The fact that fingers have markedly different strengths requires us to design an optimal keyboard layout with a tapping workload distribution close to an ideal state (Yin & Su, 2011). In this way, each finger shares an adequate amount of the workload. Deshwal and Deb (2003) argued that in the same column, keys on the home row should be given high-frequency letters and that, in the same row, keys near the center should share more hits. Apart from these directives, a relative weight of columns and rows was proposed by Wagner et al. (2003). The sequence of relative strength for each finger was evaluated as index, middle, little, ring, and thumb—from the strongest to the weakest. The proportion of workload each keystroke should share was determined by multiplying its weight coefficients of the column and the row. Note that both hands are given the same burden. All relative workloads of the ideal keyboard layout have a total sum of 1. The ideal workload distribution is shown in Figure 3.

I_1 was designed to indicate the workload distribution difference between a given layout and the ideal layout. As shown in Equation 1, $loc(i)$ gives the location of letter i on the keyboard; $f_I(location)$ gives the ideal workload distribution given by the specified location (found in Figure 3); and $f_s(i)$ gives the relative frequency of the single letter i (found in Table 6). As a keyboard layout is generated, the workload distribution difference can be calculated with Equation 1. Note that a better layout is given with a smaller I_1.

$$I_1 = \sum_{i=A}^{Z} [f_s(i) - f_I(loc(i))]^2 \tag{1}$$

Hand alternation. Alternating the use of both hands has been proven to improve typing speed and user comfort (Wagner et al., 2003). Moreover, Hiraga et al. (1980) performed an experiment to show that rhythmical typing can also improve typing speed. Hence, in Equation 2, the hand alternation rule was quantified as the second indicator by summing the relative frequency

TABLE 7
Relative Frequencies of Letter Pairs

	Second letter in the letter pair																									
	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
First letter in the letter pair																										
A	0.0001	0.0010	0.0008	0.0023	0.0002	0.0004	0.0008	0.0007	0.0144	0.0012	0.0003	0.0013	0.0012	0.0517	0.0167	0.0002	0.0005	0.0004	0.0017	0.0006	0.0000	0.0000	0.0005	0.0010	0.0016	0.0018
B	0.0038	0.0000	0.0000	0.0000	0.0020	0.0000	0.0000	0.0000	0.0046	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0048	0.0000	0.0000	0.0000	0.0000	0.0000
C	0.0014	0.0000	0.0000	0.0000	0.0005	0.0000	0.0000	0.0113	0.0014	0.0000	0.0000	0.0000	0.0000	0.0000	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0006	0.0000	0.0000	0.0000	0.0000	0.0000
D	0.0092	0.0000	0.0000	0.0000	0.0162	0.0000	0.0000	0.0000	0.0032	0.0000	0.0000	0.0000	0.0000	0.0000	0.0020	0.0000	0.0000	0.0000	0.0000	0.0000	0.0039	0.0000	0.0000	0.0000	0.0000	0.0000
E	0.0002	0.0022	0.0021	0.0035	0.0003	0.0012	0.0022	0.0018	0.0092	0.0029	0.0007	0.0022	0.0015	0.0235	0.0001	0.0005	0.0011	0.0034	0.0045	0.0014	0.0000	0.0000	0.0014	0.0025	0.0046	0.0036
F	0.0036	0.0000	0.0000	0.0000	0.0024	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0020	0.0000	0.0000	0.0000	0.0000	0.0000
G	0.0027	0.0023	0.0028	0.0060	0.0045	0.0014	0.0026	0.0023	0.0000	0.0038	0.0009	0.0029	0.0016	0.0010	0.0025	0.0006	0.0015	0.0013	0.0048	0.0017	0.0064	0.0000	0.0019	0.0028	0.0050	0.0052
H	0.0126	0.0000	0.0000	0.0000	0.0167	0.0000	0.0000	0.0000	0.0182	0.0000	0.0000	0.0000	0.0000	0.0000	0.0078	0.0000	0.0000	0.0000	0.0000	0.0000	0.0162	0.0000	0.0000	0.0000	0.0000	0.0000
I	0.0262	0.0041	0.0039	0.0079	0.0048	0.0021	0.0040	0.0038	0.0000	0.0065	0.0014	0.0044	0.0028	0.0210	0.0004	0.0009	0.0023	0.0019	0.0078	0.0029	0.0038	0.0000	0.0030	0.0039	0.0085	0.0079
J	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0203	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0032	0.0000	0.0000	0.0000	0.0000	0.0000
K	0.0020	0.0000	0.0000	0.0000	0.0020	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0012	0.0000	0.0000	0.0000	0.0000	0.0000
L	0.0033	0.0000	0.0000	0.0000	0.0045	0.0000	0.0000	0.0000	0.0085	0.0000	0.0000	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0015	0.0005	0.0000	0.0000	0.0000	0.0000
M	0.0025	0.0000	0.0000	0.0000	0.0037	0.0000	0.0000	0.0000	0.0037	0.0000	0.0000	0.0000	0.0000	0.0000	0.0018	0.0000	0.0000	0.0000	0.0000	0.0000	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000
N	0.0025	0.0025	0.0026	0.0064	0.0019	0.0012	0.0553	0.0024	0.0029	0.0040	0.0011	0.0031	0.0023	0.0011	0.0002	0.0006	0.0018	0.0013	0.0054	0.0019	0.0002	0.0003	0.0021	0.0028	0.0048	0.0058
O	0.0001	0.0014	0.0016	0.0036	0.0002	0.0008	0.0014	0.0013	0.0000	0.0019	0.0005	0.0021	0.0015	0.0134	0.0000	0.0004	0.0008	0.0007	0.0030	0.0010	0.0121	0.0000	0.0012	0.0014	0.0030	0.0030
P	0.0010	0.0000	0.0000	0.0000	0.0004	0.0000	0.0000	0.0000	0.0018	0.0000	0.0000	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
Q	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0069	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0026	0.0000	0.0000	0.0000	0.0000	0.0000
R	0.0015	0.0001	0.0001	0.0001	0.0040	0.0000	0.0001	0.0001	0.0006	0.0002	0.0000	0.0001	0.0001	0.0001	0.0005	0.0000	0.0001	0.0000	0.0003	0.0001	0.0016	0.0000	0.0001	0.0001	0.0002	0.0002
S	0.0015	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000	0.0259	0.0015	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0025	0.0000	0.0000	0.0000	0.0000	0.0000
T	0.0045	0.0000	0.0000	0.0000	0.0004	0.0000	0.0000	0.0000	0.0030	0.0000	0.0000	0.0000	0.0000	0.0000	0.0021	0.0000	0.0000	0.0000	0.0000	0.0000	0.0011	0.0000	0.0000	0.0000	0.0000	0.0000
U	0.0105	0.0020	0.0021	0.0045	0.0033	0.0011	0.0021	0.0021	0.0061	0.0029	0.0009	0.0027	0.0013	0.0048	0.0105	0.0004	0.0013	0.0012	0.0043	0.0014	0.0000	0.0000	0.0013	0.0024	0.0044	0.0042
V	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001
W	0.0024	0.0000	0.0000	0.0000	0.0053	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0022	0.0000	0.0000	0.0000	0.0000	0.0000	0.0017	0.0000	0.0000	0.0000	0.0000	0.0000
X	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0144	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0026	0.0000	0.0000	0.0000	0.0000	0.0000
Y	0.0051	0.0000	0.0000	0.0000	0.0023	0.0000	0.0000	0.0000	0.0128	0.0000	0.0000	0.0000	0.0000	0.0000	0.0061	0.0000	0.0000	0.0000	0.0000	0.0000	0.0058	0.0000	0.0000	0.0000	0.0000	0.0000
Z	0.0044	0.0000	0.0000	0.0000	0.0009	0.0000	0.0000	0.0198	0.0029	0.0000	0.0000	0.0000	0.0000	0.0000	0.0009	0.0000	0.0000	0.0000	0.0000	0.0000	0.0031	0.0000	0.0000	0.0000	0.0000	0.0000

Note. The former letter is read from the first column while the latter letter is read from the first row.

TABLE 8
Relative Frequencies of Initial Letters

Letter	Relative Frequency	Cum. Relative Frequency
D	10.35%	10.35%
Y	9.62%	19.97%
S	9.58%	29.55%
Z	9.56%	39.11%
J	7.05%	46.16%
L	5.60%	51.76%
X	5.09%	56.85%
C	4.79%	61.64%
B	4.70%	66.34%
G	4.63%	70.97%
H	4.37%	75.33%
M	3.70%	79.03%
W	3.48%	82.52%
T	3.34%	85.85%
Q	2.86%	88.71%
F	2.46%	91.17%
R	2.45%	93.62%
N	2.21%	95.83%
K	1.77%	97.60%
P	1.09%	98.70%
E	0.73%	99.43%
A	0.49%	99.92%
O	0.08%	100.00%
U	0.00%	100.00%
I	0.00%	100.00%
V	0.00%	100.00%

Note. The relative frequencies are in the descending order.

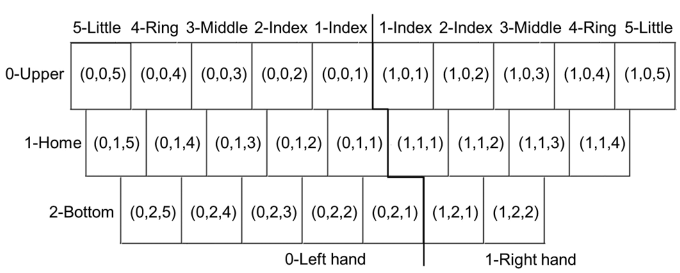

FIG. 2. Representation of a keyboard layout. *Note.* Every keystroke is represented by a unique array to show its hand usage, row and column.

of letter pairs that are typed by fingers on the same hand. $f_p(i,j)$ represents the relative frequency of letter pair (i,j) (found in Table 7) and $SH(loc(i),loc(j))$ gives 1 when the letter pair (i,j) is on the same hand. Otherwise, it gives 0 to show no penalty.

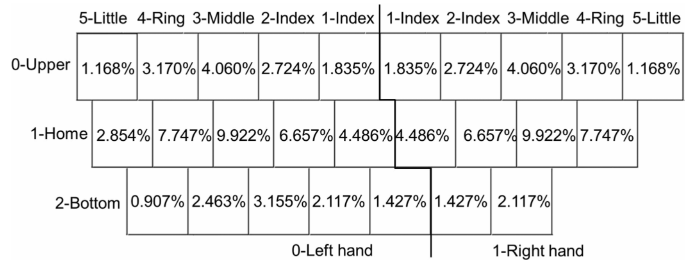

FIG. 3. Ideal tapping workload distribution of a keyboard layout.

$$I_2 = \sum_{i=A}^{Z} \sum_{j=A}^{Z} f_p(i,j) * SH(loc(i), loc(j)) \quad (2)$$

Finger alternation. Marsan (French Patent 2,611,589, 1987) held that a more comfortable tapping behavior can result from using different fingers for two consecutive letters. If this law is broken, penalty points are given proportionally to the distance of finger movement, because the larger the distance, the more inconvenient it is for a letter pair to be typed. As shown in Equation 3, the distance between two consecutive letters is multiplied with the relative frequency of the letter pair and is aggregated to be the third indicator. $SF(loc(i),loc(j))$ checks if the letter pair (i,j) is hit by the same finger and gives 1 if it is.

$$I_3 = \sum_{i=A}^{Z} \sum_{j=A}^{Z} f_p(i,j) * dist(loc(i), loc(j)) * SH(loc(i), loc(j)) * SF(loc(i), loc(j)) \quad (3)$$

As shown in Equation 4, the distance function of $dist(loc(i),loc(j))$ gives the Manhattan distance between letter i and letter j $row(loc(i))$, and $col(loc(i))$ are the second and the third elements in the location vector used to represent the layout.

$$dist(loc(i), loc(j)) = |col(loc(i)) - col(loc(j))| + |row(loc(i)) - row(loc(j))| \quad (4)$$

Avoiding big steps. Slow and laborious typing has always resulted in large distance movements with the same hand, which may require an awkward hand posture (Wagner et al., 2003). Hence, penalty points were awarded to count the occurrence probability of letter pairs that are typed on the same hand and if steps between fingers are larger than 1. The mathematical function for the fourth indicator is shown in Equation 5, where the penalty coefficients, $k(i,j)$, are suggested by Wagner et al. (2003) and presented in Table 9.

$$I_4 = \sum_{i=A}^{Z} \sum_{j=A}^{Z} f_p(i,j) * k(i,j) * SH(loc(i), loc(j)) \quad (5)$$

TABLE 9
Penalty Coefficients for Big Steps

		Second Finger			
	Thumb	Index	Middle	Ring	Little
First finger					
Thumb	0	0	0	0	0
Index	0	0	5	8	6
Middle	0	5	0	9	7
Ring	0	8	9	0	10
Little	0	6	7	10	0

Note. Source: Wagner et al. (2003). Penalty points are given to the consecutive usage of different fingers. Thumb is an exception because it is only in charge of typing spaces.

Hit direction. Wagner et al. (2003) also argued that the preferred hit direction of a letter pair on a single hand is from the little finger toward the thumb. Thus, the fifth indicator was derived to penalize letter pairs typed in the undesirable direction. As shown in Equation 6, *HD*(loc(i), loc(j)) judges whether the given letter pair is in accordance with the hit direction. If not, *HD*(*i,j*) gives 1; on the contrary, it gives 0.

$$I_5 = \sum_{i=A}^{Z} \sum_{j=A}^{Z} f_p(i,j) * SH(loc(i), loc(j)) * HD(loc(i), (loc(j)) \tag{6}$$

The overall evaluation function. The overall evaluation function is a weighted sum of indicators shown in Equation 7. The smaller the evaluation score, the better the given layout. The relative weights (shown in Table 10) between these five criteria were derived from the pairwise comparison proposed by Limayem and Yannou (2001). Because the five indicators have different units, they were divided by the respective indicators of a reference keyboard to turn dimensionless. Rather than using the QWERTY layout as a reference keyboard layout (Deshwal & Deb, 2003; Eggers et al., 2003; Wagner et al., 2003), however, the average evaluation scores of random layouts are used in this study. This is the case because the QWERTY layout is considered to be worse than average in terms of workload distribution and hit direction rules. As shown in Table 11, 1,000 keyboard layouts were generated randomly and evaluated to obtain the average score for each indicator. Results show that the change of reference layout from the QWERTY layout to the average layout would assure that the optimization objective is unbiased.

$$I = \sum_{k=1}^{5} \gamma_k * \frac{I_K}{I_{K,ref}}$$

TABLE 10
Weight Coefficients Between Indicators

Rule	y
Tapping workload distribution	0.45
Hand alternation	1.00
Finger alternation	0.80
Avoidance of big steps	0.70
Hit direction	0.60

Note. Source: Limayem and Yannou (2001). Different design guidelines have different weights.

TABLE 11
Indicator Scores of the QWERTY Layout and the Average of 1,000 Randomized Layouts

Reference Indicator	QWERTY Score	Average Score	QWERTY Performance Against Average
$I_1,_{ref}$	0.0567	0.0525	−8.0%
$I_2,_{ref}$	0.4094	0.4957	17.4%
$I_3,_{ref}$	0.1384	0.1995	30.6%
$I_4,_{ref}$	2.0073	2.5639	21.7%
$I_5,_{ref}$	0.4340	0.4105	−5.7%

Note. The smaller the evaluation scores, the better the given layout.

4.3. Genetic Algorithm

Inspired by evolutionary biology, the genetic algorithm involves a population of candidate solutions to a problem, often called individuals, which live, reproduce, and die based on their fitness relative to the rest of the population (Malas et al., 2008). As shown in Figure 4, the genetic algorithm the present study used consists of five phases: initialization, evaluation, selection, reproduction, and termination.

Initialization. Two thousand candidate layouts were generated randomly to form an initial population. The random generation kept the solution of the algorithm from a local optimum. Thus, the pool of individual layouts covered a wide

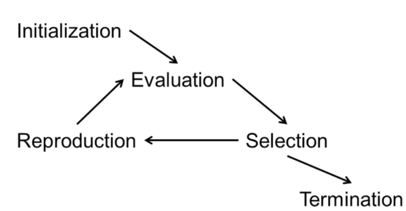

FIG. 4. Framework of the genetic algorithm. *Note.* The loop goes on until the termination conditions are met.

range of the population, and the algorithm could be applied to individual layouts until the termination condition was met.

Evaluation. In each cycle of the algorithm, an entire evaluation of the individuals was performed. A data structure of a "sorted list" was used in the process because the smaller the score, the better the layout. Thus, all individuals were sorted in ascending order, with the best layouts being first on the list.

Selection. One thousand layouts with the smallest evaluation scores lived a longer life through the "selection" process. Other layouts died and were removed from the pool. Another 1,000 layouts were generated randomly to refill the pool to 2,000. The purpose of generating random layouts in each generation was to ensure that the algorithm would not arrive at a local minimum point. Note that because the number of possible layouts was extremely huge (= 26!), the possibility of having 1,000 totally different layouts from the existing ones was $\left(1-\frac{1000}{26!}\right)^{1000} \approx 1-2.5*10^{-21} \approx 1$, which meant that totally different randomized layouts could be generated. At the same time, the algorithm also kept a record of the best layout and checked in each cycle if better layouts were obtained. A change of the best layout was recorded to track the algorithm's running status.

Reproduction. After the best 1,000 layouts were selected, another 1,000 layouts were generated randomly. All individuals went through a "reproduction" process to create a second-generation solutions that shared many of the characteristics of the parents but were different to them. In this "reproduction" process, crossover and mutation were identified as the two main operators. The rationale behind this is that the keyboard layout problem is essentially a permutation problem. Therefore a direct 1-point crossover of letter keys is not applicable. For instance, when two parent layouts exchange a part of their keys by random, it is possible that at least one keyboard will have two of the same letters, which is not a feasible solution.

Therefore the issue of crossover happens when two or more layouts engage in the "reproduction" process. To resolve this, an order crossover operator was applied. To implement this, each of the best 1,000 layouts was regarded as the parent, and through the algorithm they generate children layouts. The application behind this was first to keep part of the information from one parent stationary and then arrange the remaining information in accordance to the sequence of another parent. This created the children layouts. The order crossover used principles in randomization and switching operations. First, two to five keystrokes were randomly chosen from one parent layout. The remainder keystroke locations were kept stationary, and all passed to the children layout. To complete the keyboard layout, locations of these two to five keystrokes were randomized to mimic getting sequence from one of the other 999 best selected layouts. It was noticed that as long as the order crossover operation was done, mutation operations were also fulfilled because the two to five keystrokes were randomly selected from the parent layout. In fact, as Raynal and Vigouroux (2005) suggested, even if the mutation had decreased the individual score, it paved the way for a new search space and for a better solution in a future iteration.

Each layout, acting as a parent, generated 10 children layouts by performing the order crossover operation, which inherently combined the application of order changing mutations. Then, all layouts, including the parents and the children, were put in a pool that was later evaluated. Finally, if the termination condition was not met, the algorithm looped to the "evaluation" phase after the reproduction.

Termination. Scores of the best layouts were saved and watched carefully. The termination condition set for the algorithm was that the best layout would remain unchanged for 1,000 generations. The program was run on a 2.53 GHz Core 2 Duo computer, and it took 6 hours for the termination condition to be met. The log showed that a total of 1,161 generations, representing as many as 25,000,000 layouts, were evaluated. The curve of the best layout score was drawn against the generation number in a log scale. As shown in Figure 5, the curve converged to a minimum soon after the first 100 generations.

5. RESULTS AND ANALYSIS

5.1. Optimal Chinese Keyboard Layout

As a direct output from the genetic algorithm, the optimal layout found for Chinese is presented in Figure 6. The layout had a satisfactory global score of 1.73, which is 51.2% better than a random layout (3.55) and 43.2% better than the QWERTY layout (3.05).

5.2. Comparison and Improvement Analysis

As seen in Table 12, the new layout was compared with the current QWERTY layout. The results show that the new layout was considered better in terms of every indicator among the five Marsan's (French Patent 2,611,589, 1987) criteria, with the smallest advantage being on avoiding big steps at 18.0%, to the most significant improvement occurring on tapping workload distribution at 78.7%. Overall, the improved keyboard layout was evaluated to be 43.2% better than the QWERTY layout we use on current keyboards.

As noted, the largest improvement was in the first indicator, tapping workload distribution. As shown in Figure 6, most of the workload was shared by strong fingers, with awkward keystrokes assigned to the least frequent letters. For example, the most frequent letter, "I", was placed under the middle finger on the right hand, a location that has the most workload in the ideal distribution plan. In contrast, the most laborious location, the left-bottom corner on the left hand, was assigned the letter "F", the relative frequency of which was no more than 1.0%. Moreover, four of the top five frequent letter pairs ("N" and "G";

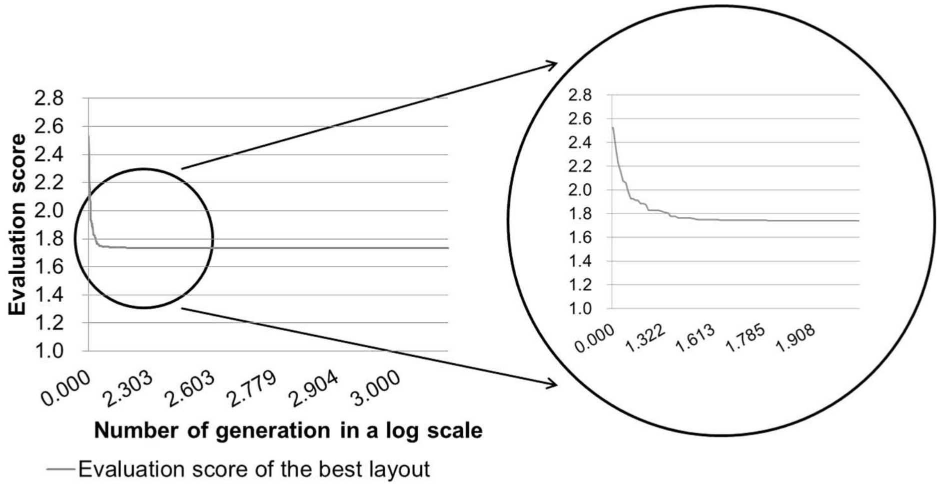

FIG. 5. Score curve of the best layout. *Note.* The evaluation score converged to a minimum soon after the first 100 generations.

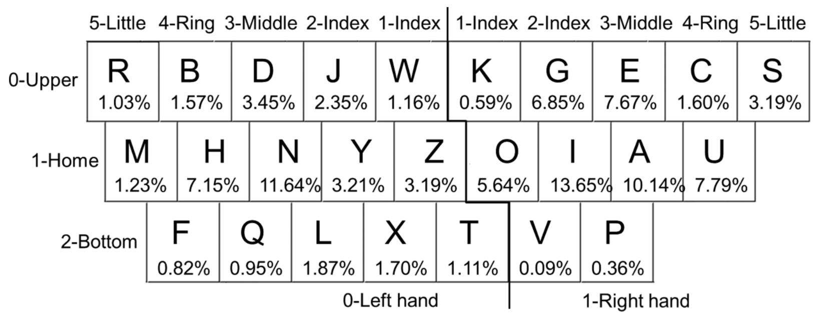

FIG. 6. The optimal Chinese keyboard layout with tapping workload distribution.

TABLE 12
Comparison of Scores Between the QWERTY Layout and the Optimal Chinese Layout

	Keyboard Layouts		
	QWERTY	Optimal	Improvement
Indicators			
I_1: Tapping workload distribution	0.0567	0.0121	78.7%
I_2: Hand alternation	0.4094	0.2810	31.3%
I_3: Finger alternation	0.1384	0.0349	74.8%
I_4: Avoidance of big steps	2.0073	1.6457	18.0%
I_5: Hit direction	0.4340	0.3227	25.6%
I: Evaluation score	3.0493	1.7315	43.2%

Note. The new layout improved on every indicator and performed 43.2% better than the QWERTY layout overall.

"A" and "N"; "S" and "H"; and "E" and "N") were typed by both hands alternatively on the new layout. The only exceptions, "I" and "A", were on the same hand. They were typed by different fingers, however, and the steps coefficient between them was relatively small. This was in accordance with the alternative finger rule and the rule to avoid big steps.

The tapping workload distribution of rows and columns of the new keyboard layout was analyzed further. As shown in Table 13, with the QWERTY layout, 43% of the typing is done on the upper row. This was highly improved with the new keyboard layout, with most of the workload (64%) performed on the home row. Thus, it is possible for the fingers to always

TABLE 13
Comparison of Workload in Rows and Columns

		Keyboard Layouts	
		QWERTY	Optimal
Row usage	0 - Upper	42.58%	29.46%
	1 - Home	36.41%	63.64%
	2 - Bottom	21.01%	6.90%
Column usage	0 - Left-hand	44.51%	42.42%
	1 - Right-hand	55.49%	57.58%

Note. The optimal Chinese keyboard layout has more workload on the home row and on the right-hand side.

stay in a natural posture. In addition, the optimal Chinese keyboard layout reduced the workload of the bottom row to 6.9%, making room for punctuation keys to be designed for the right-bottom corner. On the other hand, with the new layout, the right hand was given more work (58%) than the left hand (42%), a proportion that is similar to the DSK layout (Dvorak, 1943).

Finally, as shown in Figure 6, all vowels were placed on the right-hand side. Furthermore, the most frequent consonants, “N”, “H”, “D”, and “Y”, were placed on the left-hand side. This could be the result of the alternative hand rule. The potential advantage of keeping vowels on the same hand is that beginners may find the new keyboard easier to remember and faster to learn. Moreover, the alternating use of both hands contributed to rhythmic typing, which could improve typing efficiency and user comfort as Hiraga et al. (1980) argued.

6. DISCUSSION AND CONCLUSIONS

In the present study, a Chinese corpus having 6 million characters was analyzed with a semantic and probability-based disambiguation for polyphones. All characters were transcribed into typing script to obtain the relative frequencies of a single letter and letter pairs. A polyphone macro probability dictionary was created manually from training data, which consisted of 30,000 Chinese characters. The relative frequency of single letters in descending order was calculated as “I”, “N”, “A”, “U”, “E”, “H”, “G”, “O”, “D”, “Y”, “S”, “Z”, “J”, “L”, “X”, “C”, “B”, “M”, “W”, “T”, “R”, “Q”, “F”, “K”, “P” and “V”. The relative frequency of letter pairs is presented in Table 7. Finally, the relative frequency of initial letters (Table 8) was calculated to help further design the Chinese chord keyboard.

To solve the keyboard layout problem, each keystroke was represented by a three-element vector. Five of Marsan’s (French Patent 2,611,589, 1987) criteria—tapping workload distribution, hand alternation, finger alternation, avoiding big steps, and hit direction—were quantified as five indicators to evaluate alternatives to keyboard layout. They were turned dimensionless using the average scores of random layouts and weighted differently to yield an evaluation score. The genetic algorithm with five phases—initialization, evaluation, selection, reproduction, and termination—was applied to generate the optimal Chinese keyboard layout.

The new layout performed better than the QWERTY layout on every ergonomic indicator of Marsan’s (French Patent 2,611,589, 1987) criteria and was evaluated to be 43% better in general. It was not only more efficient but also easier to learn for users, because all vowels were placed on the right-hand side. In addition, the use of each hand was balanced, and the home row was used fully to undertake 64% of the typing workload.

It is believed that the new design of Chinese keyboard layout will greatly enhance user efficiency and comfort when typing Chinese characters. The improvement should be verified carefully with user-involved experiments (Marinaras & Lyritzis, 1993). Future research could consider including bilingual use of Chinese and English and reducing typing errors in the optimization model. The alphabetic keyboard will be also considered for keyboard layout design as a future study because switching between the alphabetic keyboard and the numeric keyboard result in slow data entries (Sears & Zha, 2010), it is also interesting to design an optimal chord keyboard layout on mobile devices using the data provided in this study.

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