A Method to Estimate Physical and Cognitive Effort in Chording Data-Entry Systems

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Abstract- **As computer technology has become ubiquitous in nature, research in text and data entry is relevant to address new user needs, according to the evolution of computing equipments and changes in user interface. This paper presents a method to estimate the physical and cognitive cost of usage for chording text-entry based systems.**

I. INTRODUCTION

While the QWERTY system [2] governs supreme as the primary text entry device for most computing systems, the evolution in computing equipments poses new challenges in man machine interfaces. Many trials have been done to address such changes. Some of them resulted in prediction algorithms, which convert numeric entries into alphanumeric characters based on statistical models. Other initiative shrinks the traditional QWERTY keyboard to a level where it would be supposed to fit for specific device models. A comparative detailed study from MacKenzie & Soukoreff [3] presents a broad list of text input techniques. It must be considered that in parallel there are investigations in course regarding the adoption of voice-speech recognition (VSR) systems. Though there are many areas where VSR would help, like speaking a name to trigger a call, or use a dictate machine to generate a text file, there are many areas where typing text can not be so easily replaced. Situations where privacy is necessary and speaking is not an option, or situations where speaking is much more complex then typing, like editing a Unix source code file, or filling up a government form for tax declaration, also require the typing based approach.

There are two major competing paradigms for text input in computer based systems: pen-based input and keyboard-based input. Both emerged from ancient technologies ("ancient" must be understood as the pre-computer era): machine-typing and handwriting.

An alternative for text entry is to explore Chord Keyboard Systems. According to Weber [1], a Chord Keyboard is a keyboard that takes simultaneous multiple key pressings at a time to form a character. In chord keyboards, the user presses multiple key combinations to enter an input instead of using one key for each character. Pressing combinations of keys in this way is called chording. Since chord keyboards require only a small number of keys, they do not need large space, nor the many keys of regular keyboards such as the QWERTY keyboard.

It is controversial to establish an ergonomic hands-on standard for Chording Systems, mainly due to the multiple ergonomic behaviors of users, differences in the environment of use and particular user preferences, so this study is not about ergonomics.

Assuming that a certain level of effort is necessary to learn and use chord keyboards, in order to achieve effective usability, this study presents a method to express effort level in terms of tangible parameters and investigate the user performance obtained from different purpose maps: minimum physical effort and minimum cognitive effort. In the section II this paper introduces the proposed method. In the section III the experimental conditions are presented, followed by the results in section IV, and finally discussion and conclusion, are presented in sections V and VI, respectively.

II. COMPOSING: THE METHOD

In order to formalize the requirements, the first step is to propose a Method for a generic chording data entry system. Assuming that chords are combinations of entry keys, they can be represented typically as a binary sequence of digits (0-released, 1-pressed). Most likely, the physical effort level will range from *minimum effort* (no key pressed or idle) to *maximum effort* (all keys pressed). Assume **K** is generic array representing a generic chording data entry system based on ***N*** entry keys. The M symbols (characters) can be expressed through M chords represented in the K array, so that M! symbol/chord pairs are possible which are called maps. Therefore each map contains the logical relation between symbols and chords.

The Effort for any given chord ***Ec(j)*** would be expressed by Equation (1) as follows:

$$Ec(j) = \sum_{i=0}^{N-1} [W(i).C(i)].T \, , \qquad (1)$$

in which **C** is the binary sequence that uniquely represents each chord, ***T*** is the total number of active keys for a specific chord ($T \leq N$), ***i*** is the array index for any given digit in **C, *j*** is the index for any given symbol in a map and ***W(i)*** is the weighted effort for a single entry key in **C.** To make it more precise ***T*** should be considered in Equation (1) since the effort is minimum for $T=0$, and maximum to $T=N$.

For any given map its respective *Map mean effort* (***Mme***) expressing the mean cost of physical usage can be determined.

Let ***P(j)*** be the probability of the ***j***th symbol represented in the map , so:

$$\sum_{j=0}^{M-1} P(j) = 1 \,. \tag{2}$$

The *Map mean effort* for a given map chosen from ***M!*** possible permutations is given by Equation (3):

$$\boldsymbol{Mme} = \sum_{j=0}^{M-1} [Ec(j).P(j)] \tag{3}$$

Choose the best combination to compose a complete symbol representation for a given Chord Keyboard **K**, including alphabet, numbers and special characters is not trivial. If the ASCII standard symbols are considered, for instance, then M should be 256 and there are 256! possible maps. This work intends to make this matter simplest as possible, for what a certain level of abstraction is proposed, where two basic symbol maps are proposed: AEOSRI map and MARCON map.

The AEOSRI map is derived from a symbol combination that minimizes physical effort (minimum Mme) according to Table I.

TABLE I
THE AEOSRI MAP

T = 1 / N * Active Bits	Individual Key Effort: Thumb 7%	Index 13%	medium 20%	ring 27%	little 33%	Chord Effort (Linear) Ec(j)	Frequency (%) P(j)	AEOSRI MAP (Portuguese): Char	Ec(j) * P(j)
0.20	1	0	0	0	0	0.0133	14.63	a	0.00195067
	0	1	0	0	0	0.0267	12.57	e	0.00335200
	0	0	1	0	0	0.0400	10.73	o	0.00429200
	0	0	0	1	0	0.0533	7.81	s	0.00416533
	0	0	0	0	1	0.0667	6.53	r	0.00435333
0.40	1	1	0	0	0	0.0800	6.18	i	0.00494400
	1	0	1	0	0	0.1067	5.05	n	0.00538667
	1	0	0	1	0	0.1333	4.99	d	0.00665333
	0	1	1	0	0	0.1333	4.63	u	0.00617333
	1	0	0	0	1	0.1600	4.74	m	0.00758400
	0	1	0	1	0	0.1600	4.34	t	0.00694400
	0	1	0	0	1	0.1867	3.88	c	0.00724267
	0	0	1	1	0	0.1867	2.78	l	0.00518933
	0	0	1	0	1	0.2133	2.52	p	0.00537600
	0	0	0	1	1	0.2400	1.67	v	0.00400800
0.60	1	1	1	0	0	0.2400	1.30	g	0.00312000
	1	1	0	1	0	0.2800	1.28	h	0.00358400
	1	1	0	0	1	0.3200	1.20	q	0.00384000
	1	0	1	1	0	0.3200	1.04	b	0.00332800
	1	0	1	0	1	0.3600	1.02	f	0.00367200
	0	1	1	1	0	0.3600	0.40	j	0.00144000
	1	0	0	1	1	0.4000	0.47	z	0.00188000
	0	1	1	0	1	0.4000	0.21	x	0.00084000
	0	1	0	1	1	0.4400	0.02	k	0.00008800
	0	0	1	1	1	0.4800	0.01	w	0.00004800
0.80	1	1	1	0	1	0.5867	0.01	y	0.00005867
								Mme	0.09951333

Therefore the AEOSRI map is a logical map based on the probabilities ***P(j)*** according to the Theory of Frequency Analysis and Information Theory [4],[6]. Notice that variations in frequency of characters are deeply influenced by language-context and there is a specific distribution for each language. On other hand, The MARCON map suggests a symbol combination that minimizes the cognitive effort (best learning curve), disregarding the level of physical effort. Despite the fact that 256! permutations are available to choose among cognitive maps, this work selected only one specially designed by the authors to be more intuitive, according to Table II.

For convention, assume minimum effort (***Min***) for a given chord ***Ec(j)=0*** when ***T=0,*** and the maximum effort (***Max***) ***Ec(j)=1*** when ***T=N***. Based on this assumptions Equation (4) is valid:

$$\sum_{i=0}^{N-1} W(i) = 1 \,. \tag{4}$$

The elements in the array **W** are expressed as a sequence of an arithmetic progression containing ***N*** elements, so any ***W(i)*** is given by Equation (5):

$$W(i) = i.\frac{2.Max}{N.(N+1)} \tag{5}$$

The present Method is expected to be useful to estimate the mean effort for generic chording systems based on ***N*** keys assuming that ***Mme*** can be calculated for any map.

TABLE II
THE MARCON MAP

T = 1 / N * Active Bits	Individual Key Effort: Thumb 7%	Index 13%	medium 20%	ring 27%	little 33%	Chord Effort (Linear) Ec(j)	Frequency (%) P(j)	MARCON MAP: Char	Ec(j) * P(j)
0.20	1	0	0	0	0	0.0133	14.63	a	0.001950667
	0	1	0	0	0	0.0267	12.57	e	0.003352
	0	0	1	0	0	0.0400	6.18	i	0.002472
	0	0	0	1	0	0.0533	10.73	o	0.005722667
	0	0	0	0	1	0.0667	4.63	u	0.003086667
0.40	1	1	0	0	0	0.0800	2.52	p	0.002016
	1	0	1	0	0	0.1067	2.78	l	0.002965333
	1	1	1	0	1	0.2933	0.01	w	2.93333E-05
	0	1	1	1	1	0.3733	1.04	b	0.003882667
	1	0	0	0	1	0.1600	0.40	j	0.00064
	0	1	0	1	0	0.1600	3.88	c	0.006208
	0	1	0	0	1	0.1867	1.28	h	0.002389333
	0	0	1	1	0	0.1867	5.05	n	0.009426667
	0	0	1	0	1	0.2133	1.67	v	0.003562667
	0	0	0	1	1	0.2400	6.53	r	0.015672
0.60	1	1	1	0	0	0.2400	7.81	s	0.018744
	1	1	0	1	0	0.2800	0.01	y	0.000028
	1	1	0	0	1	0.3200	1.30	g	0.00416
	1	0	1	1	0	0.3200	4.34	t	0.013888
	1	0	1	0	1	0.3600	0.02	k	0.000072
	0	1	1	1	0	0.3600	4.74	m	0.017064
	1	0	0	1	1	0.4000	1.20	q	0.0048
	0	1	1	0	1	0.4000	1.02	f	0.00408
	0	1	0	1	1	0.4400	0.21	x	0.000924
	0	0	1	1	1	0.4800	4.99	d	0.023952
0.80	1	1	1	1	0	0.5333	0.47	z	0.002506667
								Mme	0.153594667

III. THE EXPERIMENT

A Text Input Experiment was conducted and two different Chording maps were selected for the experiment: a minimum

Mme map, and a minimum cognitive effort map. A generic Chord Keyboard of ***N=5*** keys was chosen. These experiments were performed to measure the input speed and accuracy for text input using the chording text entry system.

A. Subject Requirements

The experiment was conducted in Brazil so selected subjects were Brazilian Portuguese native speakers. Two groups of eight people were recruited among the students body. All the subjects had previous experiences in use of computer keyboard (minimum average use of 20 minutes per day), and keypad of mobile devices for sending and storing short text messages (minimum average use of 1 time per week). Right-handed and left-handed volunteers participated.

B. Apparatus

The experiment was conducted in the usability laboratories of BenQ Mobile Brasil and UEA – Universidade do Estado do Amazonas. A single 5 key device connected to a PC computer, running a Java application on top of Windows XP, was specially designed for this experiment.

C. Procedure

The first group of students was assigned to the chord keyboard equipped with AEOSRI map while the second group was assigned to the chord keyboard equipped with MARCON map. Basic training, about three minutes, including free trial was provided for all participants. Printed helps were available through all trial sessions. Eight trial sessions per group were hold for the whole experiment cycle, 30 minutes expected for each individual session. A minimum interval time of ten minutes between sessions was mandatory for resting.

D. Test Cases

Test cases were expressed as 8 corpus growing in complexity from the first session to the last. Each corpus had up to 450 characters, including spaces, line breaks and special characters typical of Brazilian Portuguese Language. The corpora were representative of the frequency of symbols for the chosen language according to the Theory of Frequency Analysis [4],[6].

E. Metrics collection

The respective ***Mme*** for each map was calculated, though the physical cost could be expressed. The metrics were separated in two main groups: speed and accuracy. To compute speed, the time for typing was recorded. Accuracy was measured by counting errors. Text input time was later converted to input speed in terms of characters per minute (CPM) and words per minute (WPM) for statistical analysis.

F. Data Analysis

Accuracy and session duration composed the mean learning curves, though learning functions could be derived from it in order to obtain a quantitative measure for the cognitive cost. The results for each map were to verify whether there are significant differences between the learning curves for the given groups, though they were assigned to specific maps.

G. Satisfaction

A questionnaire was distributed for all participants, so user satisfaction using chord keyboard could be evaluated, based on System Usability Scale (SUS) [5].

IV. RESULTS

To measure physical effort applying the proposed Method, the ***Mme*** of 0.0995 and 0.1536 were found for the AEOSRI and MARCON maps, respectively. For SUS there was no statistically significant difference between the maps, after applying the ANOVA test with 0.05 of confidence level. In a range of 0 to 100, the SUS [5] for AEOSRI map scored up to 74 points and the MARCON map scored 64 points. As observed in Figure 1, the first derivative (slope) of the straight-line obtained after linear regression were -2.02 for MARCON and -1.79 for AEOSRI. This parameter is supposed to be somehow assigned to the learning speed, thus it will be defined as the cognitive Learning Gradient (**LG**).

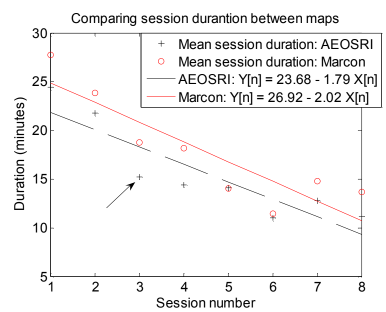

Figure 1 – The session duration between maps.. The arrows indicate statistically significant difference between maps.

The results have shown that despite the increasingly complexity through sessions for the experiment, the character accuracy and the character/word rate seemed to increase with time, what was observed for both maps.

Accordingly, it is worthwhile to investigate which map may give the best performance during user interaction with chording systems, since the AEOSRI map is supposed to give the smallest physical cost (compared to the MARCON map) while the MARCON map is supposed to give the smallest cognitive cost.

The mean character accuracy for each session is presented in Figure 2. The arrows indicate a statistically significant difference between maps, after applying the ANOVA test with 0.05 of confidence level, for the corresponding session.

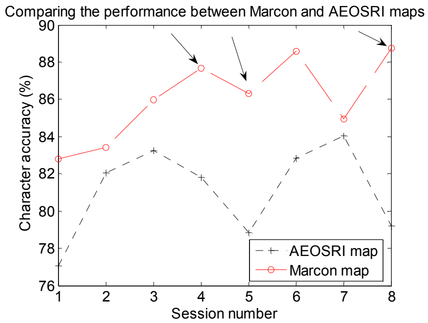

Figure 2 – The mean character accuracy for each session. The arrows indicate statistically signisicant difference between maps.

The results showed that the MARCON map outperformed the AEOSRI map at least in three sessions (including the last one) when analyzing the mean character accuracy. On the other hand, the character and word rate presented in Figures 3 and 4 have shown that the only difference between maps was observed in the first session.

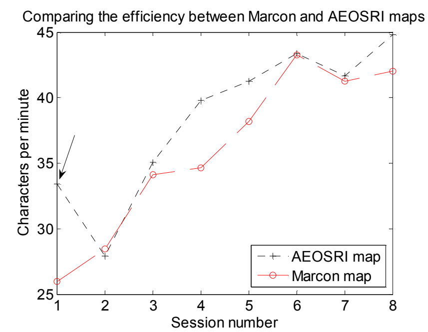

Figure 3 – The mean character rate for each session. The arrows indicate statistically significant difference between maps.

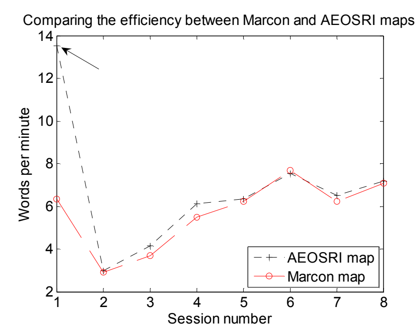

Figure 4 – The mean word rate for each session. The arrows indicate statistically significant difference between maps.

V. Discussion

Given the results, MARCON map presented superior accuracy. That could be explained by the fact that MARCON map was designed to be more intuitive and achieve better cognition. On other side, the AEOSRI map presented superior performance for CPM and WPM in the first session. This observation is possibly due to the lack of knowledge about the maps in the first session and consequently the cognitive load is apparently higher at this point. However, both maps give statistically equivalent results for the other sessions with an almost monotonic increase in efficiency, which may indicate that the cognitive cost was compensated and/or lowered after some learning period. This also suggests that the physical cost is not critical as the cognitive cost, since after the initial session both maps present the same character/word rate. Another interesting point to observe is that although there are no significant differences between mean session duration for the maps, the LG for MARCON map is higher than the rate for AEOSRI map.

VI. Conclusion

The use of traditional parameters for performance evaluation like Characters per Minute (CPM) and Words per Minute (WPM) might be useful when comparing different data entry systems, but in this particular case where different maps for the same chording data entry system were evaluated, they did not provide significant information when compared to the accuracy, the ***Mme***, or even Learning Gradient (**LG**).

As AEOSRI and MARCON maps were designed to achieve different purposes, the first - minimum physical effort, and the second - minimum cognitive effort, the satisfaction level was found equivalent from user point of view.

Future work is necessary to balance cognitive and physical effort. It would be useful to build a common map that achieves better physical performance with minimum learning effort.

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