Design of a Brazilian Portuguese Virtual Keyboard for People with Severe Motor Disability

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ABSTRACT
Virtual keyboards represent an important tool in the Assistive Technology area as they can assist in computer interaction by people with severe motor disability. Depending on the interaction method used, a differentiated arrangement of keys can speed up the task of typing a text. This work proposes a virtual keyboard layout which allows people with disabilities to write texts in Brazilian Portuguese language efficiently. The method of human-computer interaction used is a webcam-based cursor controller limited by continuum vertical and horizontal movements. Keys arrangement is based on digraphs frequency of occurrence in a corpus of Portuguese language. The performance of the virtual keyboard was evaluated by two tests. Firstly, a function which estimates the movement efficiency when typing a key is used to compare the layout with other solutions. Proposed layout presented typing speed faster than QWERTY (41%), OPTI (4%) and FITALY (3%). In user evaluation, users have performed the tasks significantly faster with the proposed keyboard layout.

Author Keywords
Virtual Keyboard; Accessibility; Text entry; User Interface Design and Evaluation.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces---Interaction styles; H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces---Ergonomics; K.4.2. Computer and society: Social Issues---Assistive technologies for person with disabilities.

INTRODUCTION

Assistive Technology (AT) is an interdisciplinary area of knowledge which comprises products, resources, methodologies, strategies, practices and services whose main purpose is to promote activity and participation of people with disabilities, impairments or reduced mobility, in order to obtain autonomy, independence, quality of life and social inclusion [1]. The computer is one of the main tools that can facilitate inclusion and autonomy of people with disabilities. For people who have upper limbs limitation, it is necessary the use of AT resources to aid this human-computer interaction. However, in Brazil, most of the people with severe motor disability may face access difficulties to these technologies due to its high cost of acquisition and importation or the lack of support to the Portuguese language.

In [8], a low cost solution based on ocular iris tracking is proposed as an alternative form of computer interaction for people with severe motor disability. Through the eye movement, the solution, called *cursor controller*, performs a vertical or horizontal movement to one of the following directions: up, down, left and right.

In [7], another low cost solution proposes a webcam-based video processing system that uses vertical and horizontal movements of the head to move the cursor. The system, called ROCC, or *Rastreador de Objetos para Controle de Cursor* (Objects tracker for cursor control), tracks a point between the eyes of the user (Figure 1) as a way to control the movement of the cursor. The first time this point is identified, an ellipse is fixed around it, defining the resting position (Figure 1a). The movement of the cursor starts when the user moves the mark outside the ellipse, as in Figure 1b. The click function is performed when the mouth of the user is open.

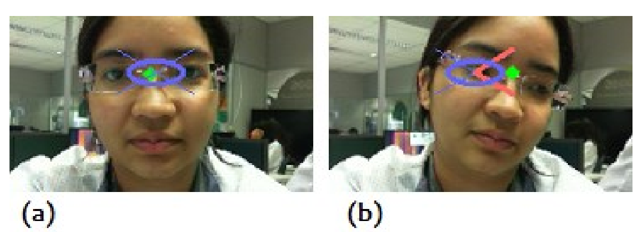

Figure 1. Webcam-based system for mouse control [7]. The cursor stays still when the green mark between the eyes (a) is inside of the purple ellipse. In (b), the green mark was moved to the right side of the ellipse, causing a continuous cursor movement to the right.

Using a webcam-based cursor controller requires an alternative method for typing a text. This task is accomplished by a virtual keyboard. However, typing without hands is not an easy activity, although increasing the size of keys and decreasing the space between them can provide an easy and smooth hands-free typing [12].

Among existing keyboard layouts, QWERTY is the most famous one. However, QWERTY layout is considered a bad choice for virtual keyboards [17] due to the most frequent pairs of letters (digraphs) are organized on opposite sides of the keyboard in order to avoid a problem called *mechanical jamming* [5] [16]. This kind of arrangement can provide very fast typing when the person uses both hands, but in a virtual keyboard, accessed by a cursor, this means frequent travels between long distances.

To solve the problem of long travels while writing a text, researchers have been developing another type of layout for virtual keyboards, which is called *optimized layout*. OPTI [10] and FITALY [15, 17] are examples of virtual keyboards which are optimized for speed up input with one finger. Both layouts were developed using Fitts' Law and characters frequency. For people with motor disabilities, EyeBoard [12] is a virtual keyboard which optimizes a frequency-based layout to be used with a cursor controlled by the movement of the eye.

Although these existing virtual keyboards can be used with the cursor controller proposed by [7] and [8], due to the fact of being optimized using the English language, the interaction may not provide the same performance when a Brazilian person is writing a text in Portuguese.

In this paper, we propose an optimized virtual keyboard layout to be used by cursor controllers limited by vertical and horizontal movements. The keyboard layout is built based on the frequency of digraphs and individual characters in order to avoid travels of long distance of the cursor. Thus, a person with severe motor disability can compose, with minimal effort, texts in Brazilian Portuguese language using only vertical and horizontal movements of cursor in a low-cost solution such as [7] and [8].

The paper is organized as follows. In the first section, it is described the methodology to construct a virtual keyboard layout for Portuguese language. The second section defines the methods of evaluation for the proposed layout. Third section shows the results of evaluation and compares with others virtual keyboard layouts. Conclusion and future work are presented in the last section.

PROPOSED VIRTUAL KEYBOARD LAYOUT

Layout optimization of a virtual keyboard consists in arrange the keys in a way that the user can type with efficiency. In other words, it is necessary to minimize the distance between the most used pairs of keys, as well as reduce the time to type a text [18].

Size in number of words	Classification
Less than 80,000	Small
80,000 to 250,000	Small-Medium
250,000 to 1,000,000	Medium
1,000,000 to 10,000,000	Medium-Big
10,000,000 or more	Big

Table 1. Corpus classification based on the size in number of words [14].

To minimize the distance between two letters (keys) in a virtual keyboard, the digraphs frequency in a specific language must be investigated. Digraphs frequency is calculated using a representative text of a chosen language, called *corpus*.

The keyboard layout is designed based on the obtained frequencies and is evaluated through a quantitative approach originally proposed in [9]. In this approach, Fitts' Law is used to estimate typing performance by calculating mean time in seconds to type a character.

Constructing a Portuguese Language Corpus

According to [11], corpus is "a large and structured set of texts, electronically stored and processed, used for a definite purpose and which is representative for the field in study." There are some relevant criteria to construct a corpus: authenticity, size, sampling, representativeness and balancing [3].

One of the most important characteristics of a corpus is its size in number of words; i.e. its representativeness to the target language is directly proportional to its size. Sardinha [14] suggests a corpus classification based on the total number of words, as shown in Table 1.

Although there are many electronic corpora of Brazilian Portuguese language [2, 4, 5, 13], due to the copyrights we could not access the full text. Hence, we chose to construct a corpus for this work. The corpus consisted of 84,251 words (464,829 characters) and was formed by the following categories of texts: academic (papers and thesis), science and technology (scientific articles), social behavior (articles related to family, well-being and relationships), encyclopedia, culture and entertainment (popular music lyrics and synopsis of movies), internet language, journalism (newspapers and magazines), religious, literature (poetries and chronicles) and technical (manuals).

Virtual Keyboard Layout Design

The layout was elaborated based on relative frequency of digraphs and individual characters present in the corpus so that characters could be placed next to its most frequent pairs. The following characters were considered when computing the frequency of occurrence: the 26 letters of alphabet, c-cedilla (ç), comma, period and space. These characters were laid out in a 5x7 matrix. The relative frequency of digraphs was calculated using (1), where the relative frequency P_{ij} is given by the ratio between the frequency f_{ij} of a pair of characters ij and the total number of digraphs in the corpus.

$$P_{ij} = \frac{f_{ij}}{\sum_{i}\sum_{j} f_{ij}} \tag{1}$$

Histograms of the relative frequency of digraphs (Figure 2) and individual characters (Figure 3) were built in order to place the keys on the matrix. In Figure 2, it was observed that the *space* character showed an individual frequency significantly superior to the others and appeared in many of the most frequent digraphs. For this reason, the key corresponding to the *space* character was placed in the central region of the matrix, occupying the entire column in order to offer easy access to and from other keys, as shown in Figure 4. The punctuation marks *comma* and *period* were placed empirically on the lower right side of *space* key since it is common to use *space* after them.

The arrangement of the other characters was made using the mean time MT to type a key (2). Equation (2), which was developed by [9] using concepts of the Fitts' Law, is defined as the sum of the movement times for all the possible digraphs, where P_{ij} is the digraph relative frequency given by (1), D_{ij} is the distance between the keys, W_j is the weight of the target key and IP is the index of performance. In this work, the distance D_{ij} is calculated by the number of keys the cursor has to travel from key i to key j using only vertical and horizontal movements. For instance, in Figure 4 the distance between a key located at (0, 2) and the comma key located at (4, 4) is D = 6. The weight W_j of the target key was defined as 1 and index performance IP was defined as 4.9, similar to [9]. Furthermore, given (2), the speed of typing in words per minute (wpm) can be obtained by (3), where 5.4 is the average characters per word in the corpus used in this work.

$$MT = \sum_{i}\sum_{j} \frac{P_{ij}}{IP}\left[Log_2\left(\frac{D_{ij}}{W_j} + 1\right)\right] \tag{2}$$

$$v = \frac{60}{5.4t} \tag{3}$$

The characters *a*, *e*, *o*, *s*, *d*, *m*, *p*, *r* and *c* which are the ones who belong to the most frequent digraphs associated with the space character were laid out around this central key at columns 2 and 4 according to the arrangement that resulted in the smallest mean time *MT* given by (2). Figure 5 shows this arrangement.

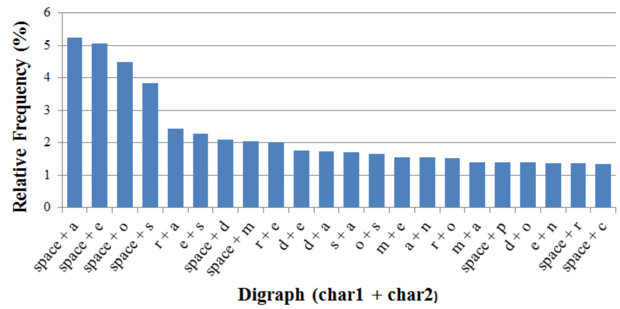

Figure 2. Relative frequency distribution of the 22 most frequent digraphs.

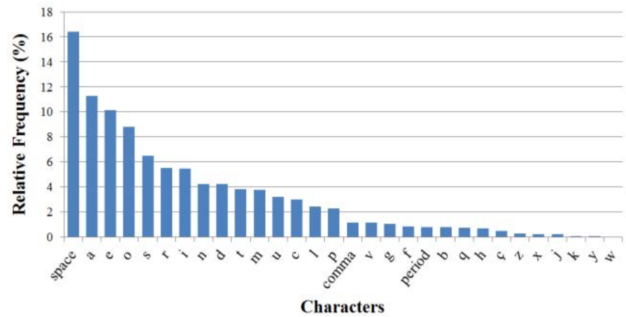

Figure 3. Relative frequency distribution of the characters.

	0	1	2	3	4	5	6
0				Space			
1							
2							
3							
4					,	.	

Figure 4. Initial matrix with the arrangement of *space*, *comma* and *period* keys. *Space* occupies the entire column 3. *Comma* and *period* are located at positions (4, 4) and (4, 5), respectively.

	0	1	2	3	4	5	6
0			C	Space	P		
1			O		R		
2			S		A		
3			E		D		
4			M		,	.	

Figure 5. Matrix with the arrangement of the most frequent characters related to *space* key.

	0	1	2	3	4	5	6
0	K		C		P		W
1	J		O		R		H
2	X		S	Space	A		Ç
3	Q	U	E		D		Z
4	Y		M		,	.	

Figure 6. Matrix with the arrangement of the least frequent characters at the columns 0 and 6. Key related to character *u* was placed between *q* and *e* due to high relative frequency of digraphs *q* + *u* and *u* + *e*.

	0	1	2	3	4	5	6
0	K	G	C		P	F	W
1	J	N	O		R	I	H
2	X	T	S	Space	A	L	Ç
3	Q	U	E		D	V	Z
4	Y	B	M		,	.	

Figure 7. Final arrangement of the virtual keyboard layout with optimized adjacent keys.

The next step comprised the least frequent characters: *w*, *y*, *k*, *j*, *x*, *z*, *ç*, *h* and *q*. After analyzing important characters related to them through digraph frequency distribution, these characters were placed on columns 0 and 6 of the keys matrix (Figure 6). Moreover, the key representing the character *u* was placed between the keys *q* and *e*, as the relative frequency of digraphs *q* + *u* and *u* + *e* is higher than other digraphs related to character *u*.

In the last step, the remaining keys *g*, *n*, *t*, *b*, *f*, *i*, *l* and *v* were evaluated in all the possible combinations and the arrangement that offered the smallest mean time MT was chosen for the final layout (Figure 7).

LAYOUT DESIGN EVALUATION

The evaluation of the proposed layout design comprises two tests. The first evaluation compared the mean time (2) to type a character when writing a text using four different virtual keyboard layouts, including the proposed layout. The second evaluation measured the time spent by users to type small phrases when the same virtual keyboards as in the first test.

All the evaluations were executed in a desktop computer with a 3.2GHz Intel Xeon processor and a 17" widescreen LCD monitor with a 1680x1050 resolution. Keyboard layout interfaces and evaluation functions were written in Java. Layouts were represented as a matrix of characters and the graphical user interface (GUI) for each keyboard presented the same key size (except Space key), background color and text size, as shown in Figure 8, Figure 9, Figure 10, and Figure 11. For the user tests, it was used ROCC, the cursor controller described in [7]. User images were captured using a Microsoft LifeCam HD-5000 webcam.

Performance Evaluation

In the first evaluation, a performance test was performed in order to compare the time spent to type a text when using four different layouts: the proposed layout (Figure 8), QWERTY layout, OPTI layout [10] and FITALY layout [15]. For the QWERTY layout presented in Figure 9 as a matrix, it was used a variant layout defined by the Brazilian National Standards Organization (*Associação Brasileira de Normas Técnicas – ABNT*) which contains the character ç. Figure 10 and Figure 11 show the representations of OPTI and FITALY keyboards.

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

Figure 8. Graphical interface of the proposed layout for virtual keyboard.

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

Figure 9. Graphical interface of a Brazilian variant of QWERTY layout which includes the character *ç*.

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

Figure 10. Graphical interface of the OPTI layout.

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

Figure 11. Graphical interface of the FITALY layout.

Since OPTI and FITALY keyboards were based on English language, they do not contain the character *ç*. Another difference is the absence of the punctuation marks *comma* and *period*. Thus, two tests were executed in this evaluation.

For Performance Evaluation 1, which included the four layouts, character *ç* was replaced by character *c* and punctuation marks were omitted from the text. Performance Evaluation 2 used only the proposed layout and QWERTY layout, therefore no alterations were made in the text.

The two tests of this evaluation used a second corpus which was constructed with a different and smaller set of texts written in Portuguese language. Equation (2) was used to obtain the mean time to type a character and (3) was used to calculate typing speed. It was considered a rate of 5.4 characters per word.

User Evaluation

In the second evaluation, five volunteers were asked to use the same four layouts to type small phrases. Among the volunteers, one of them is a person with upper limbs disability. Regarding their experience using the cursor controller, two volunteers considered themselves experienced users, since they use this device for more than two years. Two volunteers, who had already used the device before, considered themselves intermediate users. One volunteer had never used the cursor controller before.

Similarly to the performance evaluation, two tests were executed, one using only *a* to *z* letters and the other including letter ç and the punctuation marks. In both user evaluations, the order of the tested keyboards was aleatory. Due to the lack of *Backspace* key in all virtual keyboards, users were instructed to ignore the typing errors when writing a phrase. In a questionnaire applied at the end of each test day, users were asked to sort the tested layouts by preference.

User Evaluation 1 consisted in measure the time spent to execute the task of typing a phrase containing 29 characters (including *Space*). For 5 days the users executed this task using each keyboard, four phrases a day. Initially, 48 phrases were selected from several texts. Five phrases were drawn from this set for each keyboard.

User Evaluation 2 was similar to the first user evaluation, although it was realized only with the layout developed in this work and the Brazilian QWERTY layout. For this test 8 phrases containing 29 characters were randomly selected from texts. The phrases included each of the following characters: *ç*, *comma* and *period*. For 4 days, volunteers tested 1 phrase per layout.

RESULTS AND DISCUSSION

In Performance Evaluation 1, (2) and (3) were used to obtain the mean time to type one key and the text typing speed (in words per minute) for the four layouts presented in Section 3. The results are shown in Table 2. QWERTY layout variant presented the worst speed when typing the evaluation text corpus, providing a writing rate of 24.9296 words per minute. OPTI and FITALY layouts obtained a similar performance, with speed of 33.6802 and 34.0623 words per minute, respectively. The best performance was presented by the proposed layout in this work, with mean time of 0.3164 seconds and text typing speed of 35.1173. This layout is approximately 41% faster than QWERTY layout, 4% faster than OPTI layout and 3% faster than FITALY layout.

Results for Performance Evaluation 2 are shown in Table 3. Our optimized layout presented mean time of 0.3186 seconds to type a key, providing a writing rate of 34.8748 words per minute, which shows an increase of 41% relative to the text typing speed of the Brazilian QWERTY layout when the text contains characters as *ç*, *comma* and *period*.

These results show that the performance of our layout remains the same in both cases: using or not the characters *ç*, *comma* and *period*. This behavior is observed with the Brazilian QWERTY layout as well. This little change in the time spent when typing the two types of texts can be explained by the low frequency of these characters, as it is shown in Figure 3.

For User Evaluation, the layout developed in this work allowed users to type the given phrases faster than other layouts. Table 4 shows the mean time of each user when using the keyboards during five days of test. Using (3), we estimated the typing speed for each user (Figure 12).

Keyboard layout	Mean time (seconds)	Speed (words per minute)
Brazilian QWERTY layout	0.4457	24.9296
OPTI layout	0.3299	33.6802
FITALY layout	0.3262	34.0623
Proposed layout	0.3164	35.1173

Table 2. One-key typing mean time and text typing speed for virtual keyboards, excluding *ç*, *comma* and *period*.

Keyboard layout	Mean time (seconds)	Speed (words per minute)
Brazilian QWERTY layout	0.4487	24.7629
Proposed layout	0.3186	34.8748

Table 3. One-key typing mean time and text typing speed for virtual keyboards, including *ç*, *comma* and *period*.

Keyboard layout	Mean time (seconds)				
	User 1	User 2	User 3	User 4	User 5
Proposed layout	100	93	148	96	95
OPTI layout	116	103	170	120	100
FITALY layout	111	107	159	100	96
Brazilian QWERTY layout	127	141	148	124	104

Table 4. Mean time to type a small phrase for each volunteer in User Evaluation 1.

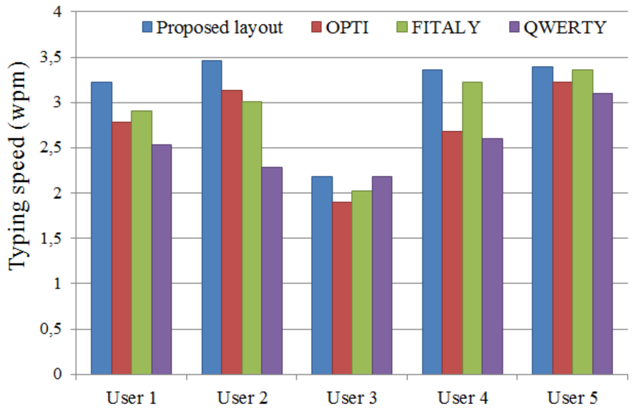

Figure 12. Results of User Evaluation 1 with the typing speed for each user, using the webcam-based cursor controller ROCC.

Keyboards	Typing speed *ts*		t-Student value t
	$\overline{ts}$	σ	
Proposed layout versus OPTI	-0.3807	0.1903	-4.474
Proposed layout versus FITALY	-0.2186	0.1663	-2.940
Proposed layout versus QWERTY	-0.5832	0.4529	-2.879

Table 5. Performance analysis of the proposed layout on User Evaluation test.

To verify the performance of our layout compared to the other layouts, we applied the t-Student hypothesis test. The null hypothesis is H_0: $\mu_d = 0$, where μ_d is the difference between the speed of a layout (QWERTY, FITALY or OPTI) and the speed of our layout. Thus, H_0 is rejected if the calculated value t is greater than the critical value t_c. Using a confidence interval of 95% and 4 degrees of liberty, we have a critical value t_c of -2.132. Table 5 shows mean values and standard deviation of each speed comparison between our layout and the others. In Table 5, it is also shown the resulting value t of the one dimensional t-Student test. Given that all values are greater than the critical value t_c, users have performed the tasks significantly faster when using our keyboard layout.

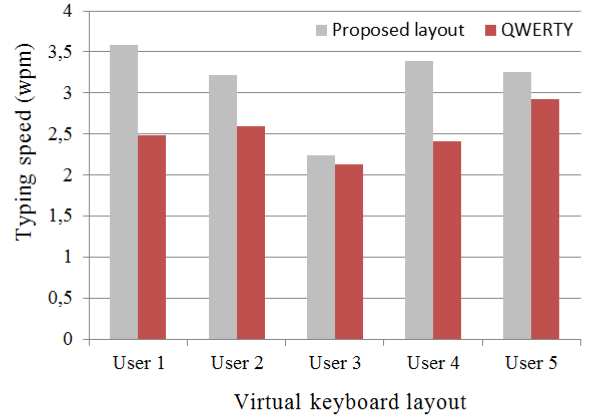

Figure 13. Results of User Evaluation 2 with the typing speed for each user, using the webcam-based cursor controller ROCC.

When asked in the questionnaires about which keyboard they preferred, our layout was chosen as the best keyboard more times (14 times) than others, despite the little mean time difference between this layout and FITALY. OPTI was chosen 6 times; FITALY was chosen 4 times; and QWERTY, only 1 time. According to users, the proximity of digraphs in our layout had facilitated the search for the next character to be typed. In their opinion, for FITALY and OPTI keyboards, this proximity was affected due to the presence of more than one Space key in the middle of the keys. Regarding to QWERTY layout, the search for keys was not a problem, as the volunteers were familiar with this arrangement. However, the great horizontal distance between the most common digraphs provided more effort from the user. Therefore, this keyboard was the worst evaluated by users, being chosen 12 times as the worst layout. OPTI and FITALY were chosen 9 and 4 times, respectively. In this evaluation, our layout was not chosen as the worst layout for any user.

User Evaluation 2 tested only keyboards with character ç and punctuation marks. Individual results are shown in Figure 13. For the layout proposed in this work, all users presented better performance than QWERTY when typing phrases containing the aforementioned characters. The average time spent by users when typing the given phrase was approximately 106 seconds for our layout and 130 seconds for QWERTY layout.

Compared to User Evaluation 1, most of users presented a better performance when using the proposed layout. On the other hand, QWERTY provided a longer time to write phrases containing *ç*, *comma* and *period*. One of the reasons for the increase of time can be attributed to the position of key a, which is the character that appears more times next to letter ç. In a QWERTY keyboard, these two characters are on opposite sides of the keyboard. In this second evaluation, when asked about which keyboard they preferred, all users chose our layout in the days of test.

CONCLUSION AND FUTURE WORK

This work presented the development of a virtual keyboard layout for people with severe motor disability. The layout was optimized with the objective of minimize cursor travels when writing texts in Brazilian Portuguese language. To control the cursor, we used a low cost solution based on image processing of a webcam [7] which performs movements only on vertical and horizontal directions.

We used the most common digraphs in Portuguese language to lay out the letters on the proposed virtual keyboard. *Space* key presented a significantly high relative frequency; therefore this key was placed in the middle of the keyboard with a differentiated size. Punctuation marks *comma* and *period* were empirically positioned next to *Space* key.

Performance and user evaluation showed that our layout provided better results when compared to other optimized virtual keyboard layouts and QWERTY layout. Although our layout improvement seems to be small compared to the other keyboards, volunteers evaluated it positively when asked which keyboard they preferred. Furthermore, a keyboard designed for Portuguese language must have the special character *ç* which is absent in English-based layouts.

With the keyboard developed in this work, it is possible to write Portuguese language texts that includes the character *ç*, with reduced effort and typing time. Besides *ç*, there are other special characters that are often used in this language, such as the diacritical marks acute, grave, tilde and circumflex that are written over some vowels. Thus, we propose as future work to evaluate the arrangement of these diacritical marks in the virtual keyboard.

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