VNU Journal of Science: Com. Science & Com. Eng., Vol. 41, No. 2 (2025) 1-15

VNU Journal of Science:
Computer Science and Communication Engineering

Journal homepage: http://www.jcsce.vnu.edu.vn/index.php/jcsce

Original Article

Multi-Layer Virtual Keyboard Interface Based on Character Frequency for Vietnamese BCI Speller System

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Received 25th November 2024
Revised 12th September 2025; Accepted 10th December 2025

Abstract: The BCI (brain-computer interface) speller system comprises essential components, including hardware for recording brain signals and software for processing these signals. EEG (Electroencephalography) sensors record brain activity, which is then analyzed to classify into specific commands for character selection by the software. The software's GUI (Graphical User Interface) facilitates user interaction by displaying the necessary symbols.

This article focuses on the design of a virtual keyboard interface aimed at efficiently selecting Vietnamese characters for text composition in the BCI spleller system. Our contributions include a multi-layered keyboard design, where keys are organized based on functional groups and the ***frequency*** of character usage in Vietnamese. The multiple layered keyboard features keys that represent individual Vietnamese character, groups of related characters, or functional keys for specific editing tasks.

In our Vietnamese BCI speller system, EEG signals are captured using the EPOC Flex. During EEG signal processing, we employ a Linear Discriminant Analysis (LDA) classifier with motor imagery tasks involving right-hand and foot movements. Experimental results with our virtual keyboard interface indicate that without suggestions, the typing rate achieved was 2.37 characters/min, which improved to 6.15 characters/min when suggestions were utilized, demonstrating the effectiveness of our design.

Keywords: BCI Speller, Virtual keyboard, Vietnamese keyboard.

1. Introduction

Recently, BCI researchers have developed various applications that benefit patients with Motor Neuron Disease (MND), with the BCI speller applications gaining significant attention [1-4]. The applications allow users to

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https://doi.org/10.25073/2588-1086/vnucsce.4084

communicate through a GUI displaying letters, numbers, symbols, and functional keys. It captures and analyzes brain signals, enabling users to select characters by focusing on them or imagining their selection, rather than pressing physical keys.

The BCI speller system consists of essential hardware and software components. The hardware includes devices for recording brain signals and transmitting them to a computer, which processes these signals while running the user interface software. Key components include EEG sensors that record brain signals, a signal processing program that analyzes these signals to identify patterns and classify commands, and a GUI that displays characters for selection. Users interact with the GUI by focusing on the characters or using other methods to choose their desired input. Each component is crucial for creating an effective communication experience, highlighting the importance of integrating technology with user interface design for seamless interaction.

In this article, we present a layered design for a virtual keyboard interface, with key arrangements based on functional groups and the frequency of Vietnamese characters. This design enhances the efficiency of composing Vietnamese text in a BCI speller system, integrated with a functional Vietnamese language model. Each layer features selectable keys, with their positioning and character selection based on usage frequency in text composition and editing.

2. Related Works

Several designs for BCI spelling systems in English have emerged. Since the number of selectable keys for composing text in English is relatively small, the design process is consequently simpler.

The RSVP Speller (Rapid Serial Visual Presentation Speller) [5] is a spelling device that uses BCI technology. In this system, characters are displayed sequentially on the screen in a rapidly flashing format, enabling users to concentrate on the target character they want to select. The system relies on event-related potentials, particularly the P300 signal, for character identification. When the target character appears, it generates a distinctive signal in the brain. Some versions of the RSVP Speller may utilize color or groups of characters to enhance accuracy and facilitate user recognition.

The P300 spelling device [6] is a BCI system that utilizes P300 brain waves to assist users with disabilities in communicating by spelling letters or symbols. It typically employs an oddball matrix model, where symbols flash randomly on the screen. Users focus on their desired symbol, and when it flashes, their brain emits P300 waves, recorded via EEG. The signals are analyzed to identify the P300 wave and determine the intended symbol, enabling communication without physical means through a user-friendly interface. Researchers are continually working to improve spelling accuracy and speed.

GeoSpell [7] is another BCI-based spelling tool that uses an N × N matrix, like a 6 × 6 grid, to optimize character identification. The layout is organized into sets of 2 × N square frames for easier recognition. Rows and columns are rearranged into separate boxes, allowing the target character to be identified by classifying the sets it appears in, minimizing eye movement. GeoSpell employs eye-tracking technology for character selection, though its performance has yet to match that of traditional BCI spelling devices.

Block Speller [8] is a BCI-based device that displays characters or words in blocks that flash or change color to stimulate the P300 response. Users select a character by focusing on the corresponding block for a set duration, enabling the system to identify their choice. Block Speller has shown performance comparable to, or even better than, other BCI spelling devices due to its intuitive design.

CakeSpeller [2] is a spelling system using BCI technology, featuring a visually engaging interface resembling a cake, with characters organized into "slices." This design helps users easily recognize and select characters. The system leverages the P300 response; when users focus on a specific slice, it triggers a neural response for character recognition. Its intuitive interface reduces stress and fatigue during communication, enhancing both speed and accuracy compared to traditional spelling devices.

CenterSpeller [9] employs a character matrix arranged around a central point. Users focus on the character they want to select, and the system identifies it based on the P300 response. Surrounding characters flash or change to attract attention, making selection easier. By looking at a character for a set duration, users allow the system to confirm their choice. CenterSpeller improves communication speed and accuracy through its visual design and advanced technology.

3. Proposed Design of a Virtual Keyboard Interface

In designing virtual keyboards, particularly for BCI-speller systems, several key factors must be taken into account [10]. These include key positioning, which can adopt matrix or circular shapes, and key size, which may be fixed or variable. Symbol distribution is essential and should be based on a language corpus that accurately reflects the language, considering factors such as frequency, logical arrangements (e.g., A-Z or QWERTY), and adaptability. The amount of symbols per key can be categorized as ambiguous (1:1 key to symbol) or unambiguous (1: many keys to symbols), with distribution being either homogeneous (the same number of symbols for each key) or heterogeneous (varying numbers of symbols per key). The total number of keys may vary in ambiguous systems but is ultimately constrained by the character count in the alphabet (e.g., 2, 4, 8, …). Feedback mechanisms can be audible (sounds upon selection) or visual (e.g., flashing symbols or highlights). Scanning methods can encompass various styles, including linear, row and column, three-dimensional, and containment hierarchy, functioning in either automatic or manual modes. Actions following selection may involve snapping back to the home interface or remaining persistent, while shorter delay times can accelerate typing but may also lead to increased errors. Additionally, special characters must be considered.

For the Vietnamese language, which features a vast array of characters and tonal marks, the number of selectable keys can approach 200. This underscores the significance of designing an effective keyboard for the BCI-speller system tailored to composing Vietnamese text. In this section, we analyze the complexities of the Vietnamese language and present our solutions for creating a virtual keyboard that enhances text composition efficiency."

3.1. Components of Vietnamese Text Composition

The standard Vietnamese alphabet, as defined by the Vietnamese Ministry of Education [11], consists of 29 letters, which include 17 single consonants: b, c, d, đ, g, h, k, l, m, n, p, q, r, s, t, v, x; 12 single vowels: a, ă, â, e, ê, i, o, ô, ơ, u, ư, y; 10 digraphs: ph, th, gi, tr, ch, nh, ng, kh, gh, and ngh; 3 diphthongs, which can be represented in various ways: ia-yê-ie, ua-uô, ưa-ươ; and 5 tonal marks: acute accent (/), question mark (?), grave accent (\), dot (.), and tilde (~).

To form a numeric string, 10 digits are necessary: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9. For composing Vietnamese sentences, we normally require 13 punctuation marks: period (.), comma (,), question mark (?), exclamation mark (!), semicolon (;), colon (:), parentheses (()), hyphen (-), ellipsis (…), dash (_), single quote (‘’), quotation marks (“”), and slash (/).

In designing the virtual Vietnamese keyboard interface, we organized characters into parent and child categories based on their meanings, creating a hierarchical structure that considers letter frequency in text composition. This ensures that (i) characters with similar functions are grouped together, and (ii) higher-frequency characters are placed lower in the hierarchy for quicker selection.

Additionally, four control function keys are used during composition: delete, line break (enter key), back (to return to the previous layer in case of a selection error), and space.

3.2. Arguments for the Proposed Design Method of the Virtual Keyboard Interface

The virtual keyboard interface is defined as an interactive workspace with three areas (Figure 1): Area 1 displays edited text, Area 2 contains selection keys for text composition, and Area 3 shows suggested characters/words. Each interface layer is assigned a natural number, with lower numbers appearing first. Higher-numbered layers are accessed when keys from smaller-numbered layers are expanded.

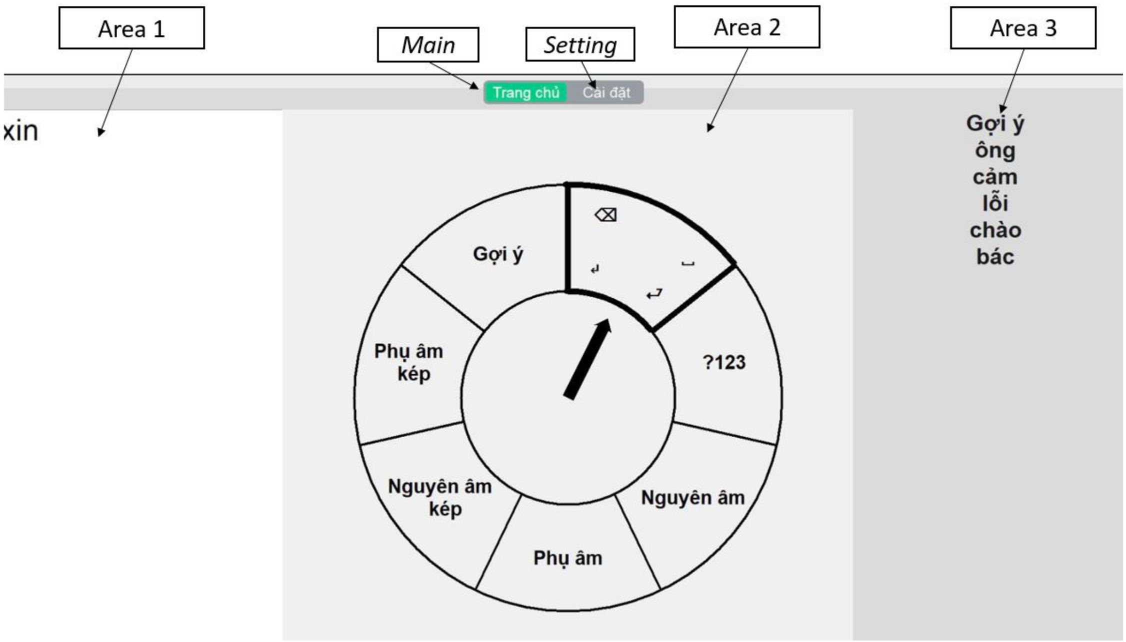


Figure 1. Areas of the workspace and virtual keyboard.

Area 2 includes buttons for characters, character groups, and functional keys, enabling users to compose text or perform actions like deleting or line break using brain signals. The interface is organized into multiple layers, enhancing selection efficiency through a frequency-based approach, where frequently used characters require fewer actions. Keys are designed with simple shapes, colors, and symbols for quick selection, including all Vietnamese characters and essential editing functions. This method optimizes key selection for Vietnamese text input using EEG signals, prioritizing common characters in lower-numbered layers to minimize selection actions. The proposed keyboard will include a complete set of 12 single vowels, 17 single consonants, 4 basic control functional keys for text editing, 10 digraphs, 3 diphthongs, 5 tonal marks associated with the single vowels and diphthongs, as well as 10 numeric characters. The control functional keys include *Delete, Line Break, Back,* and *Space*, to facilitate the text editing process. The proposed virtual keyboard interface integrates a Vietnamese language model that suggests relevant characters and words based on the content being composed, improving the efficiency of text editing. It features a suggestion function key that provides context-aware character and word recommendations. Below are frequency tables from Stefan Trost Media's research [12], detailing the single vowels (Table 1) and consonants (Table 2) used in designing the Vietnamese virtual keyboard.

Table 1. Frequency of Vietnamese single vowels

No	Character	Frequency	No	Character	Frequency
1	A	9.45%	7	Ê	2.77%
2	I	6.94%	8	Ơ	2.43%
3	O	4.27%	9	Â	1.89%
4	U	3.92%	10	E	1.88%
5	Ô	3.67%	11	Y	1.56%
6	Ư	2.79%	12	Ă	1.14%

Table 2. Frequency of Vietnamese single consonants

No	Character	Frequency	No	Character	Frequency	No	Character	Frequency
1	N	11.02%	7	M	2.98%	13	K	1.32%
2	H	7.96%	8	R	2.32%	14	P	1.06%
3	C	6.72%	9	V	2.12%	15	D	0.88%
4	T	6.61%	10	L	1.90%	16	Q	0.34%
5	G	5.29%	11	S	1.56%	17	X	0.33%
6	Đ	3.10%	12	B	1.50%			

The proposed method of interface layering addresses the challenge of displaying the extensive range of Vietnamese characters. The BCI speller translates EEG signals into key selections across layers, using a rotating pointer that moves to indicate no selection and stops to signify a chosen key. To accommodate the uneven distribution of character groups, the number of keys on each layer is arranged flexibly in a circular layout around the pointer, ensuring even time distribution, inspired by the Hex-O-Spell interface [13]. Each key can switch between circular and arc shapes for aesthetic appeal, allowing for configurations of 4 to 9 keys per layer.

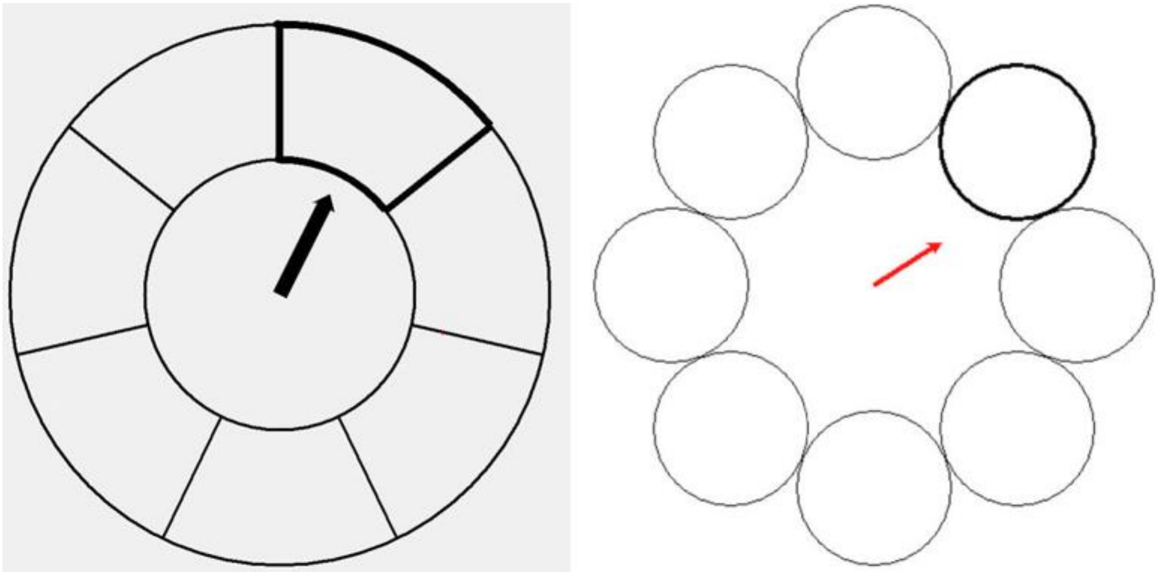


Figure 2. Layout of the virtual keyboard.

Figure 2 shows two key shapes: a four-corner arc key (left) and a circular key (right) on the interface layer. The size of each layer can be adjusted to small, medium, or large, accommodating different screen sizes and user preferences. Users can customize the background, pointer, and key colors. Characters and symbols are arranged according to Vietnamese standards and user interface design principles, including single vowels, consonants, diphthongs, digraphs, numeric characters, tonal marks, and punctuation. If a character group is not fully displayed, an expand key will open a new layer for that group. Characters with higher frequencies, are prioritized in lower-numbered layers, requiring fewer selection actions. Control keys are represented by familiar symbols.

The virtual keyboard operates by analyzing EEG signals to classify them based on predetermined imagined movements. Each movement intention corresponds to a control signal that stops the rotating pointer at each key for selection. Each key can represent a selected character, a control function, the opening of a higher virtual interface, or a word suggestion from the integrated Vietnamese language model.

3.3. Designed Virtual Keyboard Interfaces

The virtual keyboard is organized into four layers based on the grouping of characters by function and frequency. It has Layer 1 with 1 interface, Layer 2 with 5 interfaces, Layer 3 with 7 interfaces, and Layer 4 with 20 interfaces, along with 1 interface for control keys and 1 for suggested characters/words.

The proposed control functional key interface, L_Func, includes four functions: Line Break, Back, Delete, and Space. It also features a suggestion interface, L_sug, which integrates a language model to provide characters and words suggestions from Layers 2 to 4, depending on user input. These are numbered according to the LiGDj rule: “Layer i Interface j” indicating the j-th interface of Layer i.

Figure 3 shows Layer 1, the main interface, which has 7 keys: one for control functions, one for numeric characters and punctuation, and others for vowels, consonants, diphthongs, digraphs, and the suggestion function. The control functional key is available on all layers.

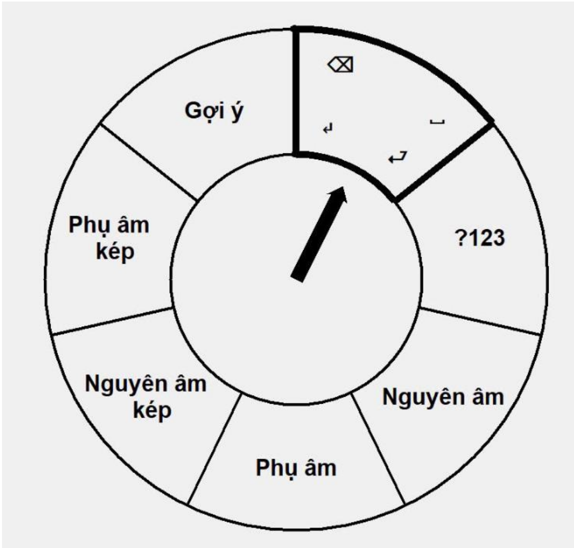


Figure 3. Layer 1 interface.

Selecting the control functional key on any layer opens the control interface ***L_func*** in the next layer. Figure 4 (left) shows this interface, which includes 4 keys: Line Break, Enter (to return to the previous interface), Delete (to remove the selected character), and Space.

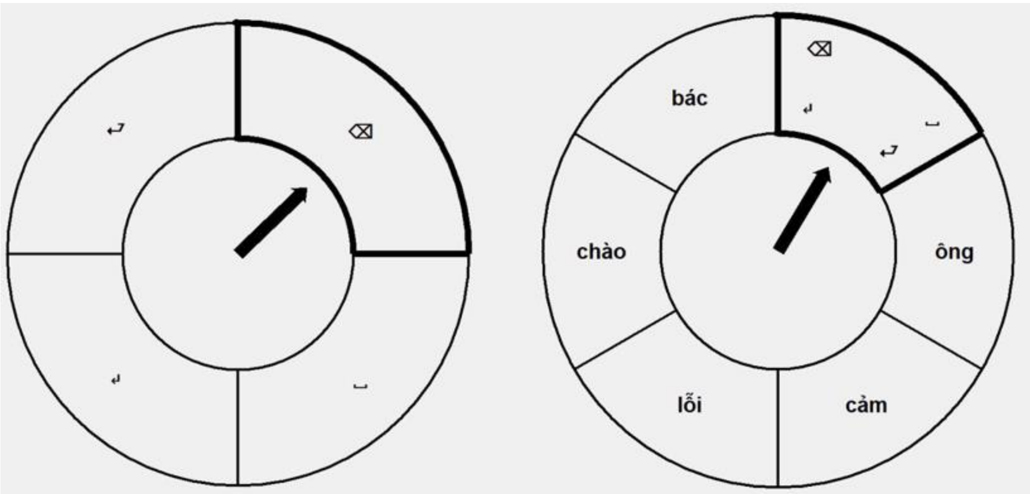
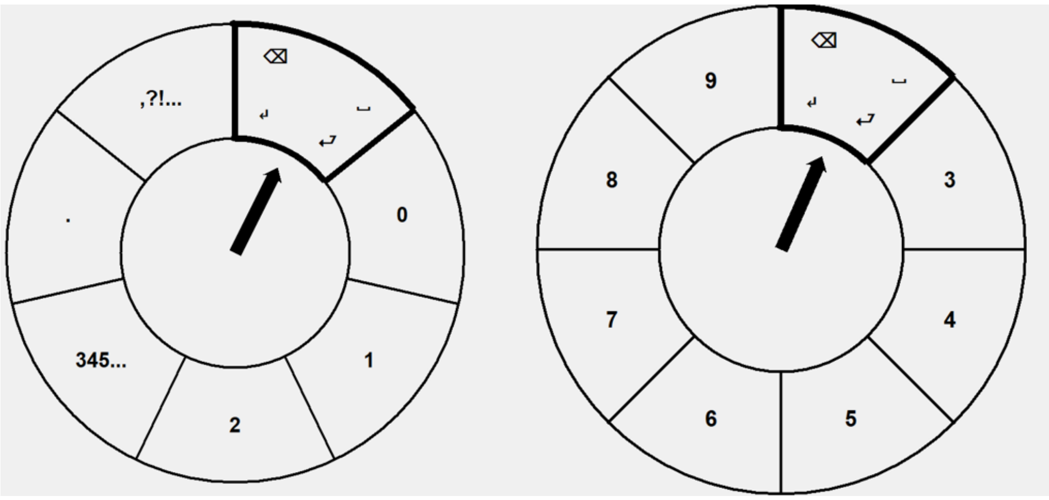


Figure 4. Control Interface and Suggestion.

Selecting the suggestion key on any layer opens the suggestion interface ***L_sug*** in the next layer. Figure 4 (right) displays this interface, which includes 7 keys: the control functional key and 6 keys for characters/words suggested by the Vietnamese language model, corresponding to the 6 words shown in Area 3 of the previous interface.

Selecting the key for numeric characters and punctuation on the Layer 1 interface opens the L2GD1 interface. Figure 5 (left) illustrates the L2GD1 interface, which comprises 7 keys: the control functional key, keys for characters 0, 1, and 2, an extended numeric key for additional characters, a period (.) key, and an extended punctuation key for additional marks.



Figuer 5. L2GD1 and L3GD1 Interfaces.

Selecting the extended numeric key on the L2GD1 interface opens the L3GD1 interface. Figure 5 (right) shows the L3GD1 interface, which includes 8 keys: the control functional key and keys for numeric characters 3 to 9.

Selecting the extended punctuation key on the L2GD1 interface opens the L3GD2 interface. Figure 6 (left) illustrates the L3GD2 interface, which consists of 7 keys: the control functional key, comma (,), question mark (?), colon (:), hyphen (-), ellipsis (…), and exclamation mark (!).

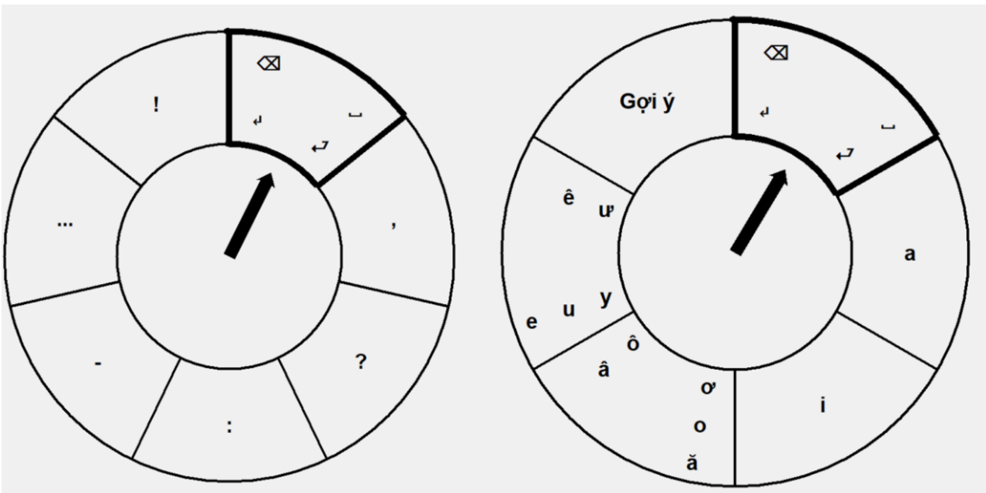


Figure 6. L3GD2 and L2GD2 Interfaces.

Selecting the vowel key on the Layer 1 interface opens the L2GD2 interface. Figure 6 (right) shows the L2GD2 interface, which includes 6 keys: the control functional key, keys for characters i and a, an extended vowel key 1 for (ă, â, o, ô, ơ), an extended vowel key 2 for (e, ê, u, ư, y), and the suggestion function key.

Selecting the extended vowel key 1 on the L2GD2 interface opens the L3GD3 interface. Figure 7 (left) displays the L3GD3 interface, which consists of 7 keys: the control functional key, 5 keys for characters ă, â, o, ô, ơ, and the suggestion function key.

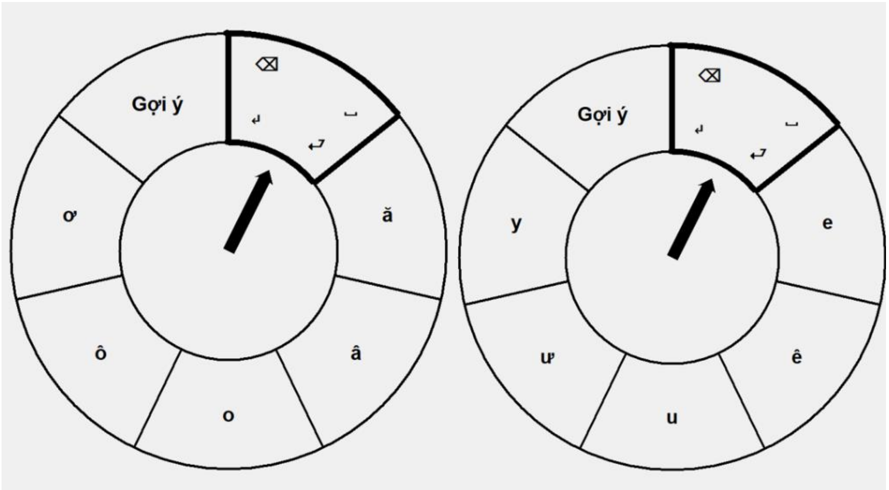


Figure 7. L3GD3 and L3GD4 interfaces.

Selecting the extended vowel key 2 on the L2GD2 interface opens the L3GD4 interface. Figure 7 (right) shows the L3GD4 interface, which includes 7 keys: the control functional key, 5 keys for characters ký, e, ê, u, ư, y, and the suggestion function key. Selecting the consonant group key on the Layer 1 interface opens the L2GD3 interface. Figure 8 (left) illustrates the L2GD3 interface, which contains 8 keys: the control functional key, keys for characters n, h, c, t, g, an extended consonant key 1 for additional consonants, and the suggestion function key.

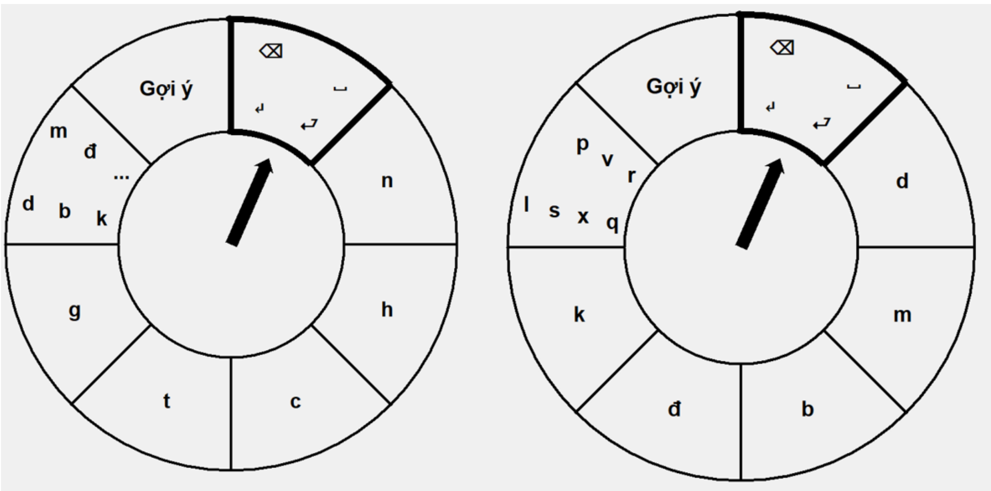


Figure 8. L2GD3 and L3GD5 interfaces.

Selecting the extended consonant key 1 on the L2GD3 interface opens the L3GD5 interface. Figure 8 (right) shows the L3GD5 interface, which has 8 keys: the control functional key, keys for characters d, m, b, đ, k, an extended consonant key 2 for additional consonants, and the suggestion function.

Selecting the extended consonant key 2 on the L3GD5 interface opens the L4GD1 interface. Figure 9 (left) presents the L4GD1 interface, which consists of 9 keys: the control functional key and keys for characters l, p, s, v, x, r, q, along with the suggestion function key.

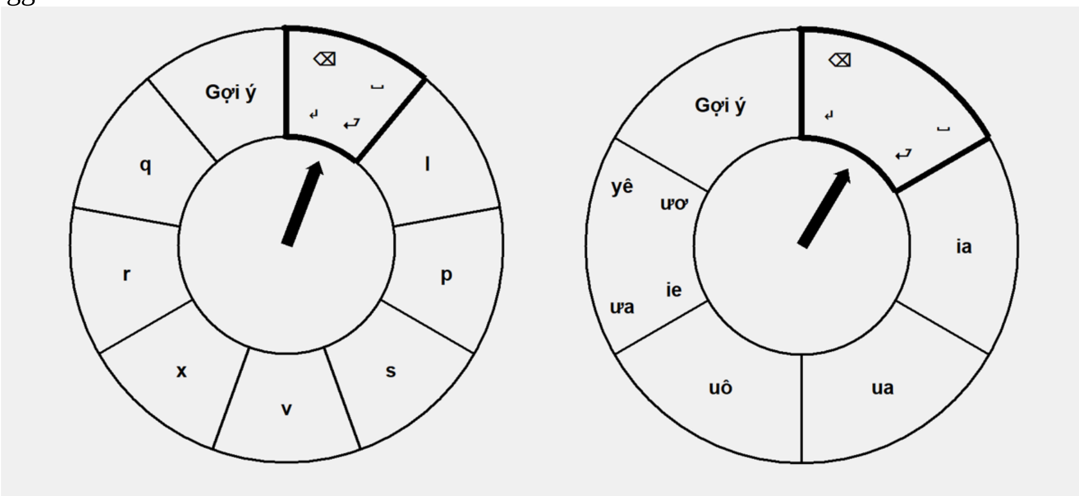


Figure 9. L4GD1 and L2GD4 interfaces.

Selecting the diphthong key on the Layer 1 interface opens the L2GD4 interface. Figure 9 (right) shows the L2GD4 interface, which contains 6 keys: the control functional key, keys for diphthongs ia, ua, uô, an extended diphthong key for additional options, and the suggestion function key. Selecting the extended diphthong key on the L2GD4 interface opens the L3GD6 interface. Figure 10 (left) displays the L3GD6 interface, which includes 6 keys: the control functional key and keys for diphthongs ưa, yê, ie, ươ, plus the suggestion function key.

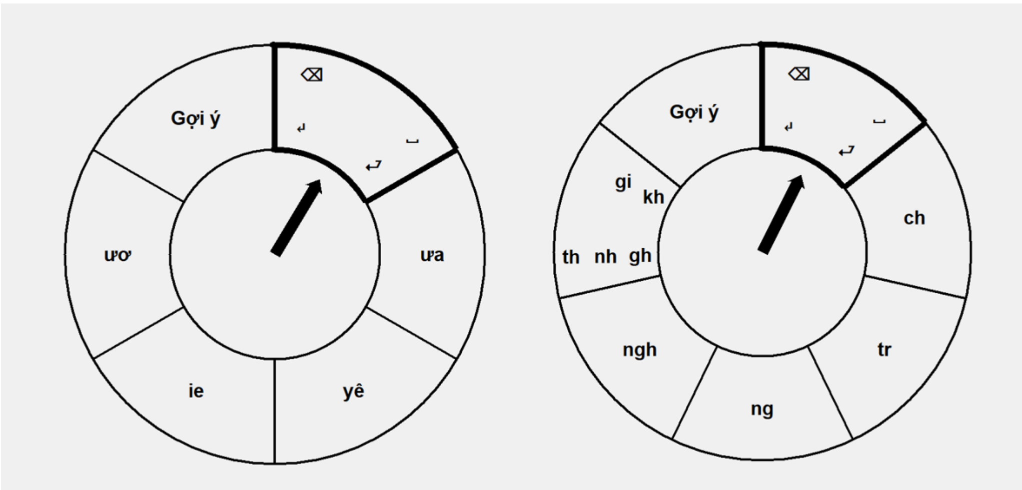


Figure 10. L3GD6 and L2GD5 interfaces.

Selecting the digraph key on the Layer 1 interface opens the L2GD5 interface. Figure 10 (right) shows the L2GD5 interface, which has 7 keys: the control functional key, keys for digraphs ch, tr, ng, ngh, an extended digraph key for additional options, and the suggestion function key. When the extended digraph key is selected, it opens the L3GD7 interface. Figure 11 (left) displays the L3GD7 interface, which includes 8 keys: the control functional key, keys for digraphs ph, th, gi, nh, kh, gh, and the suggestion function key.

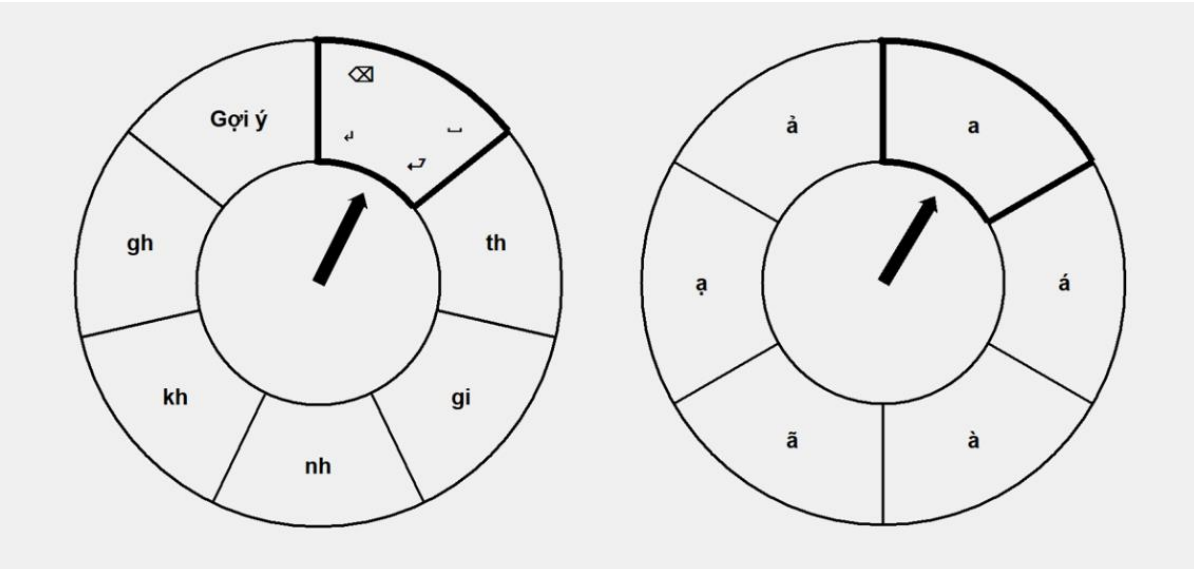


Figure 11. L3GD7 and L4GD2 interfaces.

Selecting the individual vowel keys for the 12 vowels on the L2GD2, L3GD3, and L3GD4 interfaces, as well as the 7 diphthongs on the L2GD4 and L3GD6 interfaces, opens the L4GDk interfaces, where k ranges from 2 to 20, corresponding to the selected vowel or diphthong and its tonal marks. Figure 11 (right) shows the L4GD2 interface for the character "a" and its tonal marks, which includes 8 keys: the control functional key, the vowel a key, and keys for tonal variations (á, à, ả, ã, ạ), plus the suggestion function key.

Figure 12 illustrates the relationship between layers and interfaces. The control functional interface L_Func can be accessed from any interface, while the suggestion interface L_Sug can be opened from all except L2GD1, L3GD1, and L3GD2. The L4GDk interfaces are activated when the 12 vowels and 7 diphthongs are selected on the relevant L2 and L3 interfaces.

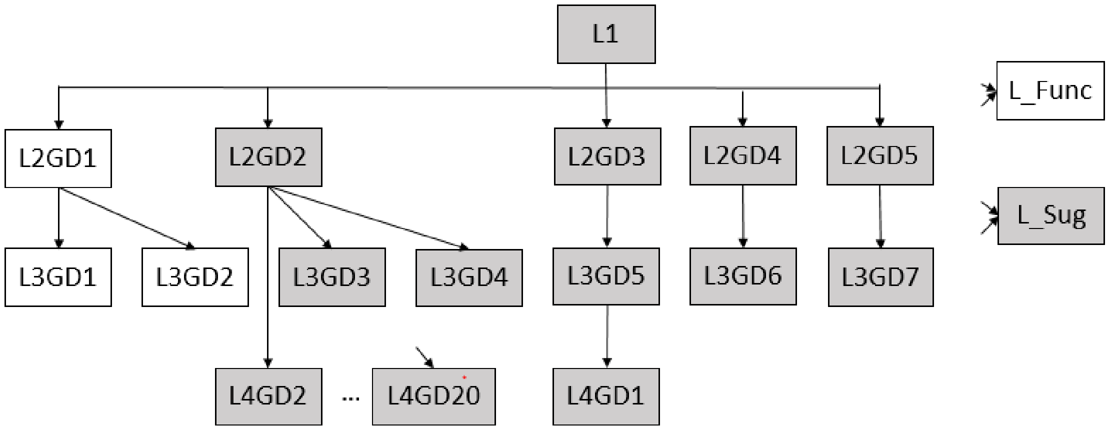


Figure 12. Relationship among the Interfaces.

4. Experiment and Evaluation

The virtual interfaces integrated into the Vietnamese BCI Speller has the following architecture (Figure 13):

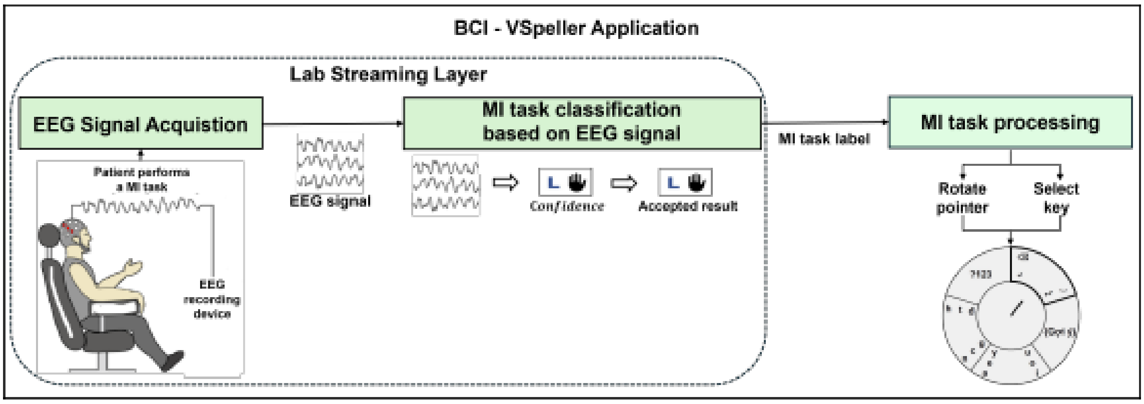


Figure 13. Vietnamese BCI Speller system.

In our system, EEG signals are collected using the EPOC Flex, a 32-channel EEG system based on EPOC+ technology from EMOTIV. During the signal labeling phase, we use an LDA classifier with MI signals from right-hand and foot tasks, applying a time window of 2.5 to 3.5 seconds and a band-pass filter of 8 to 30 Hz. The classification results are shown in Table 3, where accuracy and Cohen's kappa coefficient (κ) are defined as follows.

Accuracy (*Acc*) is the ratio of correct predictions made by the model, calculated using the following formula:

$$Acc = \frac{T}{N} \quad (1)$$

Where *T* is the number of correct predictions and N is the number of total cases.

Cohen's kappa coefficient (κ) is a widely used statistical measure for assessing agreement between two raters, particularly for imbalanced datasets. Unlike accuracy, kappa accounts for class distribution imbalances. It is calculated using a confusion matrix with the following formula:

$$\kappa = \frac{p_0 - p_e}{1 - p_e} \quad (2)$$

Where p_0 is the overall accuracy of the model and p_e is the frequency of agreement between the model's prediction and actual classification values.

Table 3. Classification result

Accuracy	**K-score**	**True-positive**	**False-positive**	**True-negative**	**False-negative**
89.04	0.7814	36	0	29	8

A key performance metric we use is the average minimum actions per character (actions/min), calculated by averaging the minimum MI tasks required to select and output a character or perform a function. In each interface, keys are arranged sequentially in a clockwise manner, following the numbering rule LiGDjKTk, where 'i' is the layer, 'j' the interface, and 'k' the character. The operation to select a character in the current interface is denoted as ki, so selecting a character is represented as $\sum_i^j k_i$.

For example, selecting the letter 'm' on L3GD5 requires a total of 14 actions: 4 actions to access the "Consonants" group in Layer 1, 7 actions to get to L2GD3, and 3 actions to reach 'm' on L3GD5. This results in an average of 13.52 actions/min, with a minimum of 2 and a maximum of 25 actions.

Another metric is characters per minute (characters/min), calculated by dividing the text length by the time taken to draft it. BCI spelling systems' performance is often measured by accuracy and **Information Transfer Rate (ITR)**, which combines accuracy and speed into a single metric expressed as the number of error-free bits per unit of time. We used the ITR calculation formula [14] as follows:

$$ITR = \frac{Acc \times N_c}{t_c} \quad (3)$$

where N_c is number of selected characters in total time t_c.

In our online experiment with participants, the tasks were to type phrases around 15-20 Vietnamese characters (for example "xin chào các bạn") which consists of 16 characters, including whitespaces. Under ideal conditions (without classifier errors, pauses, and with relevant suggestions after the first word), the typing rate would be 12.31 characters/min.

In the first scenario, without suggestions, the participants' average rate dropped to 2.37 characters/min due to classifier errors. In the second scenario, using suggestions improved performance to 6.15 characters/min.

Table 4. Comparison of the proposed interface with existing BCI systems

Interface	Shape	Actions	Layers	Choices/layers	Total Chars	Chars/min
Proposed	Circle	2 (rotate/select)	4	4 – 9	≤ 200	12.31 (ideal) 2.37 (no suggestions) 6.15 (with suggestions)
RSVP [5]	Rectangle Flashing center	1 (select)	1	30	30	1.15 – 1.43
P300 Speller [6]	Rectangle 6 x 6 grid	1 (select)	1	32	32	2.3
GeoSpell [7]	Grid (1st layer) Circle (2nd layer)	1 (select)	2	36 (1st layer) 6 (2nd layer)	36	1.38 – 1.86
Hex-o-spell [13]	Hexagons	2 (rotate/select)	2	6	30	2.3 – 7.6

Table 4 compares the proposed interfaces with four existing BCI systems based on design and performance metrics. Unlike other interfaces that support only 30–36 total characters, our interface accommodates up to 200 characters, making it significantly more versatile for real-world communication (especially for complex language such as Vietnamese). Furthermore, its circular layout, multi-layer design, and dual-action control (rotate and select) enable a real-world performance of 2.37-6.15 chars/min, far exceeding the rates of RSVP (1.15–1.43), GeoSpell (1.38–1.86), and comparable to Hex-o-spell (up to 7.6). These results demonstrate both speed and adaptability, making this design well-suited for users who need access to a broader vocabulary without sacrificing efficiency.

5. Conclusion

In conclusion, the development of the BCI speller application marks a significant advancement in communication technology for patients with MND. By leveraging brain-computer interface technology, our virtual keyboard design effectively facilitates the selection of Vietnamese characters, enhancing the text composition process. The multi-layered interface organizes keys by functional groups and character frequency, allowing for intuitive interaction tailored to the challenges faced by MND patients.

Our experimental results demonstrate the system's potential to significantly improve typing rates, especially with suggestion mechanisms. This study highlights the importance of combining user-friendly design with advanced signal processing to create a seamless communication experience.

Moving forward, further refinements and user-centered evaluations will be crucial to optimize the BCI speller's performance and usability. This research paves the way for future developments in assistive technologies, empowering individuals with MND and improving their quality of life through enhanced communication capabilities.

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