Gaze Tracking-Based Virtual Keyboard for Enhancing Communication Skills of Paralyzed Individuals

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Abstract

According to data from the World Health Organization (WHO), approximately 250 million individuals worldwide suffer from moderate to severe mobility impairments. Among these, individuals with paralysis face significant barriers in accessing digital platforms due to the limitations of traditional input methods, such as keyboards and mice, which severely restrict their ability to participate in social and digital interactions. To address this issue, this study proposes an innovative virtual keyboard system based on gaze-tracking technology. The system operates by analyzing real-time pupil movements and enabling letter selection through the user's gaze direction, with accuracy optimized through a user-specific calibration process. Experimental results demonstrate that the system achieves a high level of accuracy in text entry tasks. The primary objective of this research is to enhance digital accessibility for individuals with disabilities, thereby strengthening their independent communication capabilities and promoting greater social inclusion.

Keywords: Gaze Tracking, Virtual Keyboard, Physically Disabled Individuals, Digital Accessibility, Computer Vision, Human-Computer Interaction, Paralyzed individuals

1. Introduction

In the rapidly evolving digital age, technology has become an indispensable part of daily life, enabling communication, education, and social interaction. However, for individuals with severe physical disabilities, particularly those with paralysis, accessing digital platforms remains a significant challenge. According to the World Health Organization (WHO), approximately 1.3 billion people worldwide live with some form of disability, with 110 to 190 million adults experiencing significant difficulties in functioning [1]. Among these, individuals with paralysis due to conditions such as stroke, spinal cord injuries, or neurodegenerative diseases face unique barriers when using traditional input devices like keyboards and mice. These barriers not only restrict their ability to communicate effectively but also exacerbate social isolation, limit access to essential services, and reduce their overall quality of life [2]. Given that digital communication is a fundamental aspect of modern life, the inability to interact with digital platforms further deepens the societal divide between individuals with and without disabilities.

The concept of digital accessibility has gained increasing attention in recent years, as it plays a critical role in ensuring equal opportunities for individuals with disabilities. Digital platforms serve as essential tools for communication, education, and social participation, and the inability to access these platforms can lead to profound social, psychological, and economic consequences [3,4]. While various assistive technologies, such as speech recognition software, switch-based systems, and brain-computer interfaces (BCIs), have been developed to address these challenges, they often fall short in meeting the diverse needs of individuals with severe motor impairments. For instance, speech recognition systems are ineffective for individuals who cannot speak, while BCIs require extensive training and are often costly and inaccessible for widespread use [5,6]. These limitations underscore the urgent need for innovative, cost-effective, and user-friendly solutions that can empower individuals with disabilities to interact with digital environments seamlessly.

Eye-tracking technology has emerged as a promising alternative for individuals with limited motor function. By detecting and analyzing eye movements, this technology enables users to control digital interfaces without the need for physical input devices [7,8]. Recent advancements in computer vision and machine learning have significantly improved the accuracy and responsiveness of gaze-based systems, making them more accessible and practical for everyday use. For example, gaze-controlled virtual keyboards have been shown to enhance text entry speed and accuracy for users with motor impairments, providing a viable alternative to traditional input methods [9-11]. However, existing systems often face challenges related to calibration accuracy, response latency, prolonged usage fatigue, and adaptability to different user needs, which limit their widespread adoption and effectiveness [10,12-14].

In this study, we propose a novel gaze-tracking-based virtual keyboard system designed to address these limitations and enhance the digital accessibility of paralyzed individuals. Our system leverages real-time pupil movement analysis and user-specific calibration to optimize accuracy and responsiveness. By enabling users to select letters on a virtual keyboard through eye movements, the system aims to provide a reliable and intuitive interface for text entry. Furthermore, the system incorporates advanced computer vision techniques to minimize latency and reduce user fatigue, ensuring a seamless and comfortable user experience. Unlike existing solutions, our approach emphasizes adaptive calibration mechanisms that adjust to individual users over time, improving usability and long-term engagement.

The primary objective of this research is to improve the communication skills and social participation of paralyzed individuals by providing them with an effective tool for digital interaction. By addressing the limitations of existing assistive technologies, our system has the potential to significantly enhance the quality of life for individuals with severe motor impairments. This study not only contributes to the growing body of research on human-computer interaction (HCI) but also underscores the importance of inclusive design in the development of assistive technologies. Furthermore, the findings of this study have broader implications for the fields of rehabilitation engineering, digital accessibility, and social inclusion. By bridging the gap between technological advancements and real-world accessibility needs, this research aims to make meaningful contributions to both academia and society.

The remainder of this paper is organized as follows: Section 2 provides a comprehensive review of related work in the fields of eye-tracking technology, virtual keyboards, and assistive technologies for individuals with disabilities. Section 3 describes the methodology and design of the proposed gaze-tracking-based virtual keyboard system. Section 4 presents the experimental setup, results, and performance evaluation of the system. Section 5 discusses the implications of the findings, the limitations of the study, and potential directions for future research. Finally, Section 6 concludes the paper by summarizing the key contributions and their significance.

2. Related Work

The development of assistive technologies for individuals with disabilities has been a significant area of research in recent decades, particularly in the fields of eye-tracking technology, virtual keyboards, and HCI. Eye-tracking technology has emerged as a transformative tool in the field of assistive technologies, offering individuals with severe motor impairments an alternative means of interacting with digital devices. By detecting and analyzing eye movements, this technology enables users to control interfaces without the need for physical input, making it particularly valuable for individuals with conditions such as paralysis, amyotrophic lateral sclerosis (ALS), and spinal cord injuries. Over the past decade, significant advancements in computer vision, machine learning, and HCI have improved the accuracy, responsiveness, and usability of eye-tracking systems. However, challenges such as calibration complexity, user fatigue, and environmental sensitivity remain critical barriers to widespread adoption. This section reviews key studies in the field, highlighting their methodologies, performance metrics, and limitations, while also identifying gaps in the current literature.

Recent advancements in gaze-tracking technology have significantly improved accessibility for individuals with severe motor impairments. As highlighted in Table 1, existing systems employ various methodologies, ranging from low-cost Raspberry Pi-based solutions [15] to advanced convolutional neural network (CNN) models for gaze direction classification [18]. While these approaches demonstrate progress, key limitations persist, particularly in calibration accuracy, environmental sensitivity, and user fatigue [10,12]. Such factors hinder widespread adoption, emphasizing the need for more adaptive and robust calibration techniques to ensure usability across diverse conditions. A comparative analysis of the reviewed studies reveals a clear trade-off between accuracy and computational efficiency. Systems integrating hierarchical gaze selection [16] or multimodal inputs [19] achieve higher accuracy but often demand substantial processing power, limiting their practicality for real-time applications. Conversely, low-cost implementations [17,20] prioritize affordability but struggle with limited gaze detection precision and increased error rates. This dichotomy underscores the necessity for hybrid solutions that balance cost-effectiveness with high-performance gaze recognition. Moreover, recent studies have shifted focus toward enhancing text entry efficiency through adaptive algorithms and predictive text models [9]. However, many existing systems lack AI-driven personalization, which could optimize interaction based on individual gaze behavior. Future research should explore machine learning-based adaptive calibration, reducing user fatigue and improving typing speed. Addressing these challenges will be pivotal in developing next-generation gaze-controlled interfaces that bridge the gap between assistive technology and mainstream human-computer interaction [7,14].

Table 1: Literature Review on Gaze Tracking-Based Virtual Keyboards for Paralyzed Individuals

Study	Techniques	Features	Limitations	Contributions
Eye-Gaze-Controlled Wheelchair System with Virtual Keyboard (2022) [15]	- Raspberry Pi-based system - Eye movement and blink detection	- Low-cost solution - Integration of wheelchair and virtual keyboard	- Complex calibration process - Sensitivity to environmental lighting conditions	- Provided communication and mobility support for paralyzed individuals.
Multi-stage Gaze-Controlled Virtual Keyboard (2024) [16]	- Multi-stage hierarchical approach - Regional selection using eye movements	- Fast and accurate selection in large interfaces - User-friendly interface	- High computational power requirement - User fatigue	- Improved text entry speed and user satisfaction .
Low-Cost Eyeball Tracking Keyboard (2017) [17]	- Skin color segmentation - Support Vector Machines (SVM)	- Low-cost and high-accuracy solution - Control via three eye movements	- Limited eye movement detection capability - Sensitivity to environmental factors	- Offered an affordable communication tool for paralyzed individuals .
iGaze-Eye Gaze Direction Evaluation (2019) [18]	- Convolutional Neural Networks (CNN) - Eye gaze direction classification	- Economical and robust solution - Screen control via eye movements	- User-specific calibration required - Limited dataset availability	- Enabled text entry through eye movements .
A Multimodal Gaze-Controlled Virtual Keyboard (2016) [19]	- Multimodal approach (eye movement, head movement) - Advanced calibration algorithms	- High accuracy rate - Enhanced user experience through multi-modal interaction	- Complex interface design - High cost	- Improved the usability of gaze-tracking technology .
Eye Gaze Controlled Virtual Keyboard (2019) [20]	- 68 facial landmark detection - Selection via eye blinks	- Text entry without finger or hand use - Low-cost solution	- Errors in blink detection - Sensitivity to environmental lighting conditions	- Developed an accessible communication tool for paralyzed individuals .

3. Methodology

The proposed gaze-tracking virtual keyboard system was designed to provide an intuitive and accessible input method for paralyzed individuals. This section details the system architecture, gaze-tracking algorithm, calibration process, and text entry mechanism.

3.1 System Architecture

The system consists of three primary components: a gaze-tracking module, a virtual keyboard interface, and a text processing module. The gaze-tracking module captures and processes the user's eye movements to determine fixation points on the screen. The virtual keyboard interface is dynamically generated based on the user's gaze behavior to enhance usability. The text processing module integrates word prediction and error correction mechanisms to improve text entry speed and accuracy.

The hardware configuration includes a high-resolution webcam (1080p, 60 FPS) for real-time pupil tracking and a standard computing system equipped with an AMD Ryzen 7 7840HS processor and 16GB RAM. The software framework is implemented using OpenCV [21] for image processing and Mediapipe FaceMesh [22,23] for gaze detection.

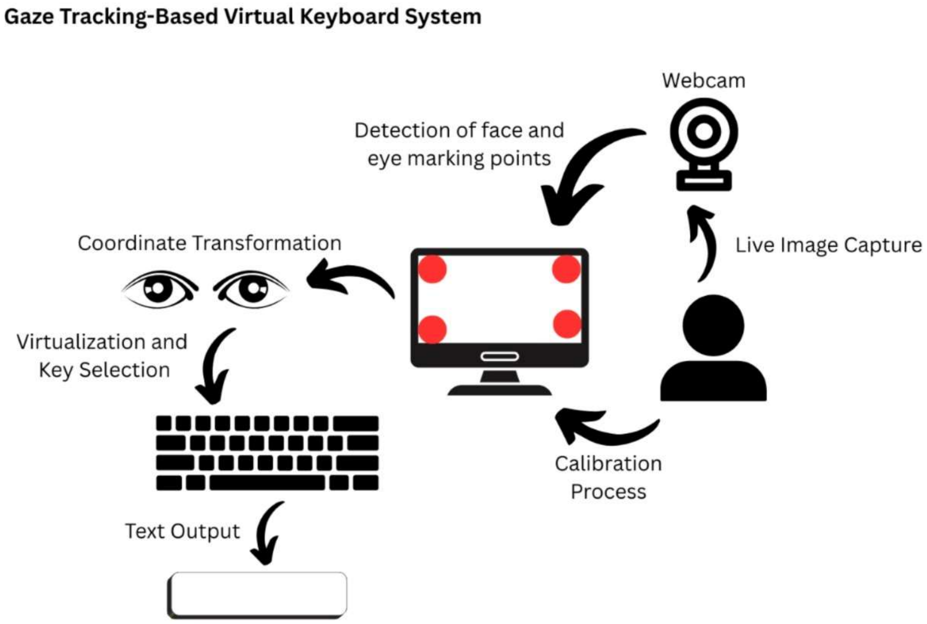


Figure 1: Proposed system's architecture

Figure 1 shows the block diagram of the proposed gaze tracking-based virtual keyboard system. Live image capture is performed via a standard webcam, followed by the detection of facial and eye landmarks. A calibration process then aligns the user's gaze with predefined screen coordinates, facilitating accurate mapping between eye position and keyboard regions. The coordinate transformation stage then converts these gaze coordinates into virtual key selections, generating the desired text output. This end-to-end pipeline is designed to provide an accessible, hands-free text entry solution, particularly advantageous for individuals with limited mobility or motor impairments.

3.2 Gaze-Tracking Algorithm

Gaze-tracking technology has evolved significantly in recent years, enabling intuitive human-computer interaction, particularly for individuals with severe motor impairments. In this study, an advanced gaze-tracking algorithm is implemented to facilitate accurate and efficient virtual keyboard interaction. The algorithm consists of five key stages: face and eye detection, pupil localization, coordinate normalization, fixation mapping, and adaptive filtering. These steps ensure robust performance, minimizing errors due to environmental factors such as lighting conditions, head movements, and involuntary eye tremors. The gaze tracking algorithm is implemented in five basic stages.

3.2.1. Face and Eye Detection

The first step in the gaze-tracking process is detecting the user’s face and extracting the eye region. This is achieved using Mediapipe FaceMesh, a state-of-the-art deep learning-based model capable of detecting 468 facial landmarks in real-time. The eye region is identified by selecting the appropriate subset of these landmarks, allowing the system to focus specifically on the user’s pupils. To determine whether the user's eyes are open or closed, the Eye Aspect Ratio (EAR) is computed using the equation (1).

$$EAR = \frac{\|P_2 - P_6\| + \|P_3 - P_5\|}{2 \times \|P_1 - P_4\|} \tag{1}$$

In the context of ocular tracking, specific key points around the eye, designated as P_1, P_2, P_3, P_4, P_5, and P_6, are utilized for data collection. A significantly low EAR value indicates a blink, whereas higher values confirm that the eyes are open and tracking can proceed.

3.2.2. Pupil Localization

After the extraction of the eye region, the subsequent step involves the detection of the pupil and the determination of its precise location. This is achieved through the implementation of image thresholding and edge detection techniques, such as the Hough circle transform. This enables the system to locate circular patterns that correspond to the pupil. The calculation of the centroid of the detected pupil is performed using the equation (2).

$$(X_c, Y_c) = \frac{\sum_{i=1}^{N} Y_i}{N}, \frac{\sum_{i=1}^{N} Y_i}{N} \tag{2}$$

In this study, the notation (x_c, y_c) is employed to denote the center of the pupil, with N representing the total number of detected pupil pixels. It is imperative to ascertain the precise coordinates, as even minor inaccuracies can result in substantial deviations in gaze tracking.

3.2.3. Coordinate Normalization

It is essential to normalize the pupil coordinates to ensure accurate mapping to the virtual keyboard, given that users have different screen sizes and distances from the display. This is achieved through calibration, where users focus on four reference points positioned at the screen corners. Figure 2 presents an example of the calibration process.

The transformation from gaze to screen is calculated using equation 3 and the Min-Max scaling method.

$$x_s = \frac{x_p - x_{min}}{x_{max} - x_{min}} \times W, \quad y_s = \frac{y_p - y_{min}}{y_{max} - y_{min}} \times H \tag{3}$$

The variables W and H are employed to denote the screen dimensions, while x_{min}, x_{max}, y_{min}, and y_{max} represent the threshold values that are obtained through calibration. This transformation ensures that gaze positions are mapped consistently across different screen sizes and user-specific variations.

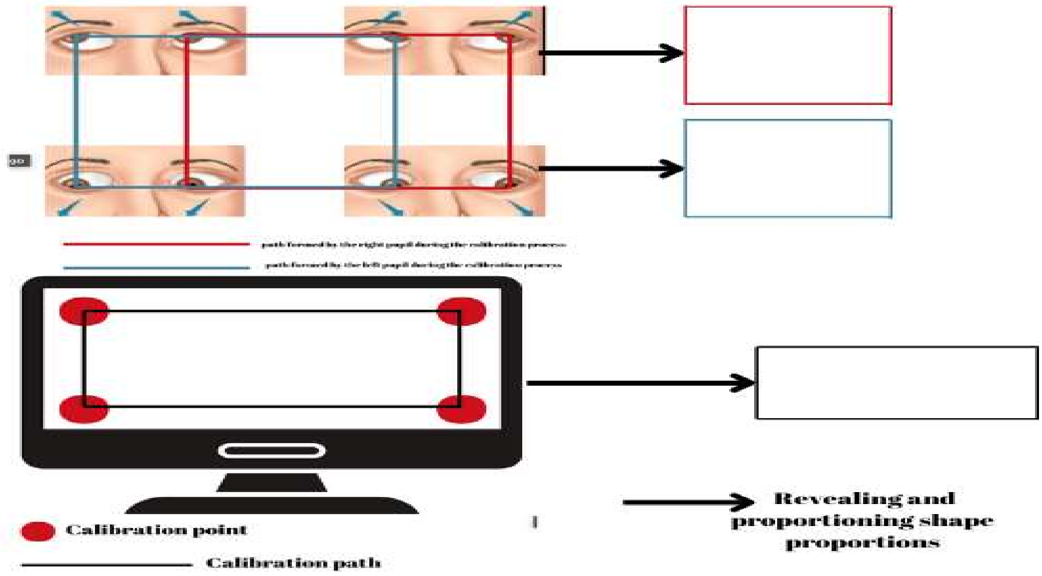


Figure 2: The calibration process

3.2.4. Fixation Mapping

The system uses a technique known as fixation mapping to prevent unintentional key selections due to rapid eye movements. This method ensures that a key is only registered if the user fixates on it for a predefined dwell time. A Gaussian weighted heatmap is then generated representing the probability of selection for each key. This probability is calculated by equation 4.

$$P(k) = \frac{\sum_{i=1}^{n} e^{-\frac{d_i^2}{2\sigma^2}}}{\sum_{j=1}^{m} e^{-\frac{d_j^2}{2\sigma^2}}} \tag{4}$$

The formula is clear; d_i is the Euclidean distance of each gaze point from the key center, and σ is the spread of the fixation region.

3.2.5. Adaptive Filtering:

Gaze tracking systems are often unstable due to involuntary saccadic movements, causing erratic cursor behavior. An adaptive Kalman filter is applied to smooth gaze transitions and correct small deviations. The filtered gaze position is updated using the state-space equation (5).

$$x_t = Ax_{t-1} + Bu_t + K(y_t - Cx_{t-1}) \tag{5}$$

The Kalman gain, K, determines how much correction is applied to the gaze estimate. The state transition matrices, A, B, and C, are known. The measured gaze position at time t is represented by y_t.

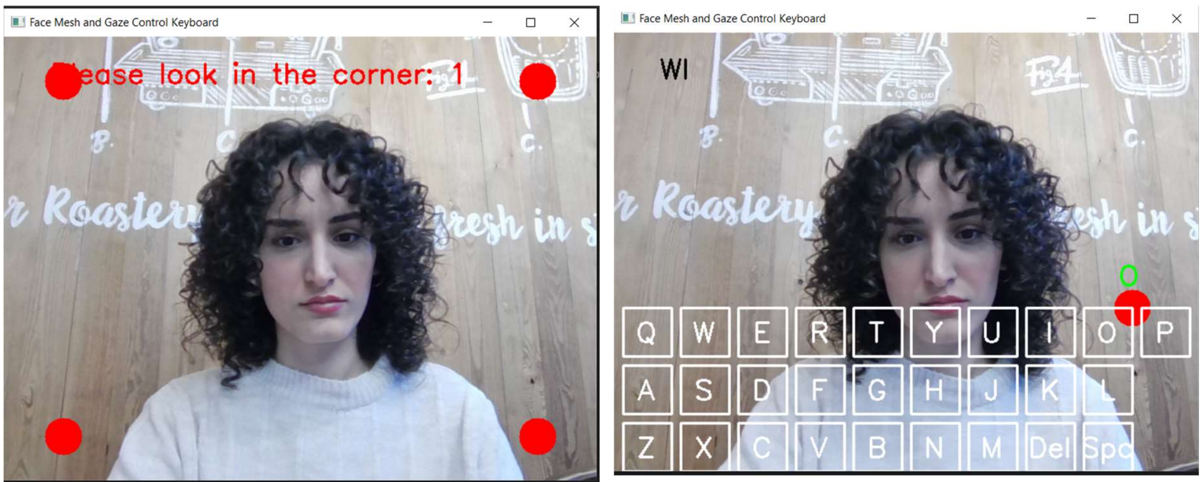
Also, eye movements may show small tremors or sudden shifts, which may lead to incorrect letter selections. To stabilize the data, a moving average filter is applied, which provides smoother transitions. The filtered pupil coordinates are calculated as in equation (6).

$$x_t = (x_{t-1} \times \alpha) + \left(x_p \times (1-\alpha)\right), y_t = (y_{t-1} \times \alpha) + \left(y_p \times (1-\alpha)\right) \tag{6}$$

To mitigate sudden shifts and micro tremors in eye movement, a smoothing filter is applied to stabilize the detected gaze coordinates. The filtered pupil position (x_t, y_t) is computed using a weighted combination of the previously recorded coordinates (x_{t-1}, y_{t-1}) and the newly detected pupil position (x_p, y_p). In the context of gaze-tracking virtual keyboards, the value of α, which is typically set to 0.8, is of paramount importance. This coefficient plays a pivotal role in prioritizing historical gaze data while seamlessly integrating new inputs. Its strategic implementation ensures the reduction of noise and unintended fluctuations, thereby enhancing the stability and accuracy of the interaction process. The efficacy of this filtering process is crucial, as it mitigates the occurrence of erroneous key selections caused by involuntary ocular micro-movements.

4. Experimental Study

The experimental evaluation of the proposed gaze-tracking system began with a dedicated calibration phase, as illustrated in Figure 3a, where the user was instructed to fixate on four red markers located at each corner of the display. This process served to map individual gaze points to specific screen coordinates, thereby enhancing subsequent tracking accuracy.

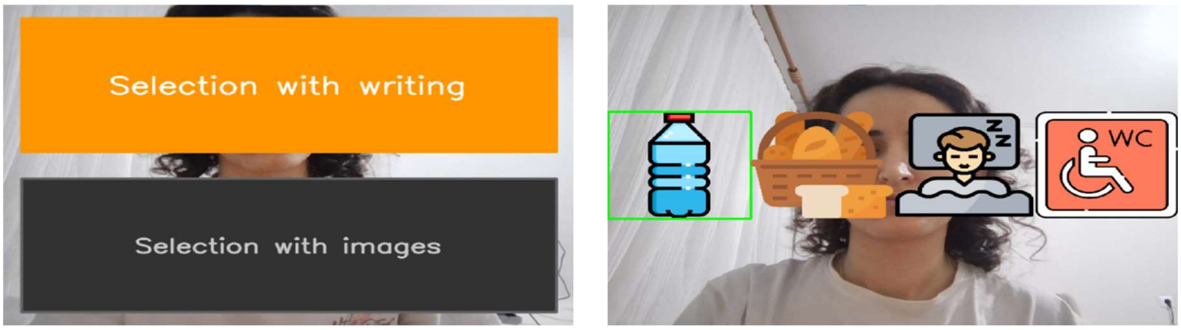


(a) (b)

Figure 3: The calibration process (a) and gaze-based virtual keyboard (b)

Subsequent to the verification of successful calibration, the system presented the participants with a virtual keyboard interface (Figure 3b). This interface enabled the participants to select letters exclusively through eye fixation. In addition to text input, the system also provided an alternative menu (Figure 4a) offering two choices—"Text Selection" (leading again to the keyboard) or "Visual Selection." If the user chose the "Visual Selection" option, a separate screen (Figure 4b) appeared, containing icons for fundamental needs such as water, meal, sleep, and restroom. By simply gazing at any icon, participants could convey essential requests without typing.

To assess system performance, preliminary trials were conducted in which participants were asked to spell out seven distinct words of varying lengths and inter-letter distances. During each session—lasting 1500 time units—several performance metrics were recorded: Accuracy, Sensitivity (True Positive Rate), Specificity (True Negative Rate), Precision, Words Per Minute (WPM), and Error Rate. Two representative performance graphs are shown in **Figure 5** (the word “sleep”) and **Figure 6** (the word “wc”).



(a) (b)

Figure 4: The gaze-tracking system menu(a) and quick selection using images (b)

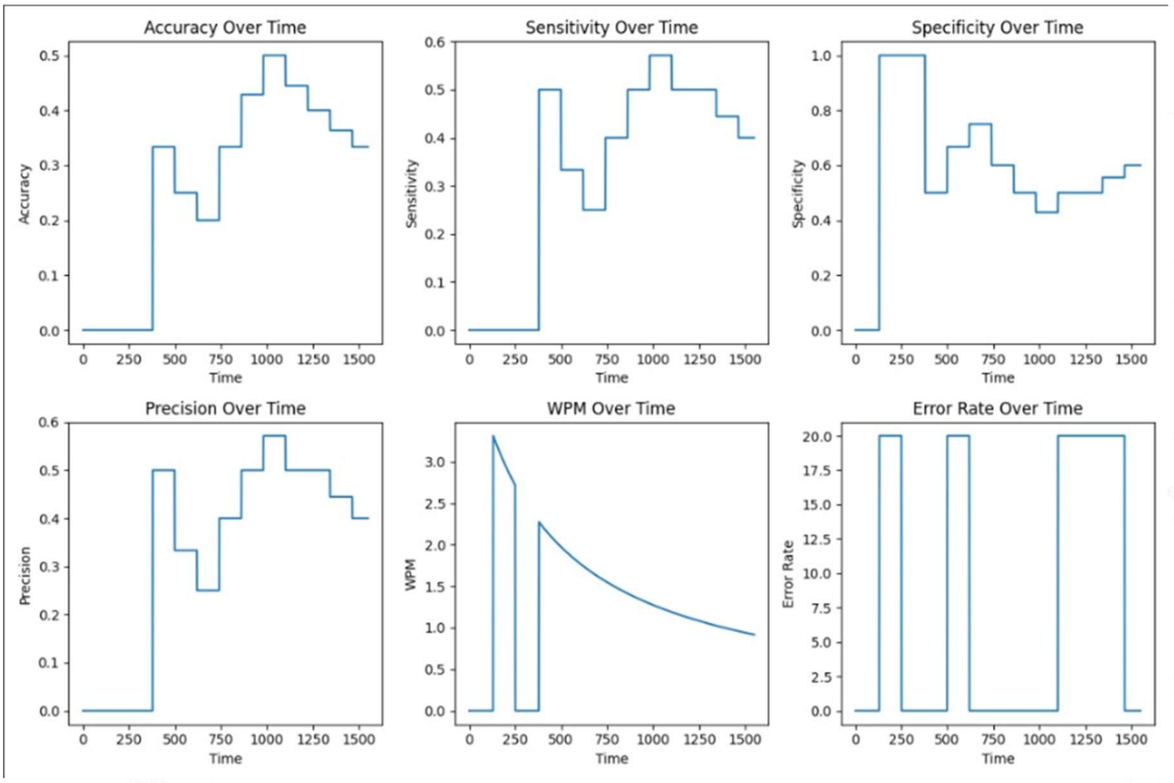


Figure 5: The performance of typing the word "sleep" with a virtual keyboard

As summarized in Table 2, shorter words composed of spatially proximate letters tended to yield higher Accuracy (0.4) and Sensitivity (up to 0.8). In contrast, when participants typed longer words or those featuring letters spaced farther apart, Accuracy could drop to 0.2, while Sensitivity declined to 0.3. Specificity also exhibited a downward trend with increasing word length—falling from 0.8 for short words to as low as 0.4 for more demanding inputs—indicating a rise in false positives. Precision followed a similar pattern, demonstrating that letter spacing and word length significantly affected the likelihood of correct key selection.

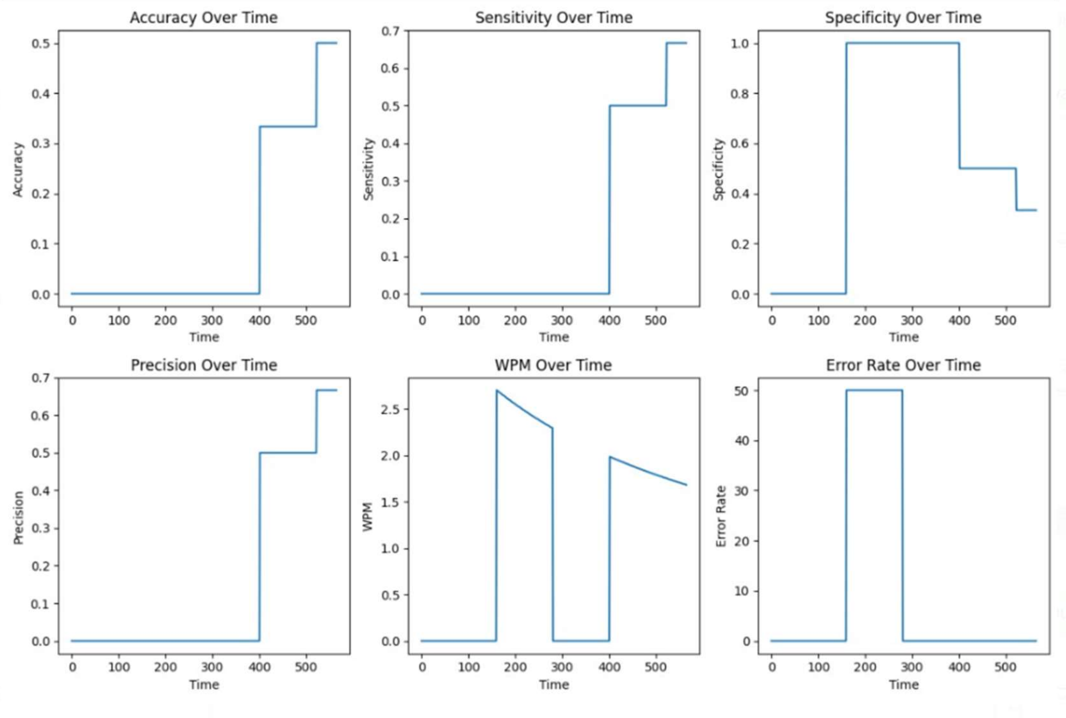


Figure 6: The performance of typing the word "wc" with a virtual keyboard

Table 2: The system performance for different words

Subjects	Number of Letters	Distance Between Letters	Accuracy	Sensitivity	Specificity	Precision	WPM	Error Rate
subject 1	2	close	0.4	0.5	0.8	0.5	2.5	50
subject 2	2	middle	0.3	0.4	0.6	0.4	2.0	60
subject 3	5	far	0.2	0.3	0.4	0.3	1.5	70
subject 4	3	close	0.1	0.2	0.2	0.2	1.0	80
subject 5	4	middle	0.7	0.8	0.8	0.8	3.0	25
subject 6	4	middle	0.7	0.8	0.8	0.8	3.0	25
subject 7	4	far	0.5	0.5	0.6	0.6	2.5	50

The WPM metric reflected the influence of word length on typing speed: shorter words allowed participants to attain speeds of up to 3.0 WPM, whereas more complex words or those with larger inter-letter distances reduced speeds to 1.5 or 2.5 WPM. Error Rate proved inversely correlated with both Accuracy and Sensitivity, approaching 50% for short words with moderate spacing but sometimes surpassing 70% in longer or more spatially dispersed words. These observations underscore the challenges associated with lengthy text input in gaze-controlled systems, primarily due to increased user fatigue and potential drift in gaze focus over time.

In sum, the findings reveal that the developed gaze-tracking software enables a viable hands-free text entry and selection process, particularly effective for basic communication. However, performance degradation for long or spatially dispersed words highlights areas requiring further refinement, such as more robust calibration strategies, advanced smoothing and filtering methods, and adaptive keyboard layouts. Future work will also focus on integrating predictive text models and AI-driven adaptations to reduce the cognitive load on users, thereby improving both accuracy and speed in complex typing tasks.

5. Conclusion

This paper represented a gaze-tracking-based virtual keyboard system designed specifically to improve digital accessibility and communication capabilities for individuals with severe motor impairments, particularly paralysis. The proposed system employs real-time pupil tracking, user-specific adaptive calibration, and advanced filtering techniques to facilitate effective hands-free text entry. Experimental evaluations demonstrated the system's practical viability, achieving promising typing speeds of up to 3 WPM and accuracy rates approaching 70% for shorter, closely-spaced words. However, system performance diminished significantly with longer words or increased inter-letter distances, indicating challenges related to gaze stability and user fatigue during extended usage.

Despite promising results, the proposed gaze-tracking virtual keyboard exhibits limitations, notably decreased accuracy and increased errors for longer words or larger letter distances, alongside sensitivity to environmental factors and user fatigue during extended use. Future research should focus on advanced calibration techniques, predictive text integration, and deep learning-based gaze estimation methods to enhance system performance, reliability, and usability in real-world applications.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

[1] World Health Organization (WHO). (2023). Disability and Health. https://www.who.int/news-room/fact-sheets/detail/disability-and-health, Access Time: 3 February 2025.

[2] Desmond, D., Layton, N., Bentley, J., Boot, F. H., Borg, J., Dhungana, B. M., ... & Scherer, M. J. (2018). Assistive technology and people: a position paper from the first global research, innovation and education on assistive technology (GREAT) summit. Disability and Rehabilitation: Assistive Technology, 13(5), 437-444.

[3] Shinohara, K., & Wobbrock, J. O. (2016). Self-conscious or self-confident? A diary study conceptualizing the social accessibility of assistive technology. ACM Transactions on Accessible Computing (TACCESS), 8(2), 1-31.

[4] Heinrich, A. J., Heitmayer, M., Smith, E., & Zhang, Y. (2024). Experiencing Hybrid Spaces A scoping literature review of empirical studies on human experiences in cyber-physical environments. Computers in Human Behavior, 108502.

[5] Huggins, J. E., Moinuddin, A. A., Chiodo, A. E., & Wren, P. A. (2015). What would brain-computer interface users want: opinions and priorities of potential users with spinal cord injury. Archives of physical medicine and rehabilitation, 96(3), S38-S45.

[6] Brannigan, J. F., Liyanage, K., Horsfall, H. L., Bashford, L., Muirhead, W., & Fry, A. (2024). Brain-computer interfaces patient preferences: a systematic review. Journal of Neural Engineering.

[7] Novák, J. Š., Masner, J., Benda, P., Šimek, P., & Merunka, V. (2024). Eye tracking, usability, and user experience: A systematic review. International Journal of Human–Computer Interaction, 40(17), 4484-4500.

[8] Shi, Y. (2024, June). A Bibliometric Analysis of Eye Tracking in User Experience Research. In International Conference on Human-Computer Interaction (pp. 178-193). Cham: Springer Nature Switzerland.

[9] Hamid, A., & Kristensson, P. O. (2024). 40 Years of Eye Typing: Challenges, Gaps, and Emergent Strategies. Proceedings of the ACM on Human-Computer Interaction, 8(ETRA), 1-19.

[10] Severitt, B. R., Castner, N., & Wahl, S. (2024). Bi-Directional Gaze-Based Communication: A Review. Multimodal Technologies and Interaction, 8(12), 108.

[11] Zhang, C., Liao, H., & Meng, J. (2025). Evaluating the performance of gaze interaction for map target selection. Cartography and Geographic Information Science, 52(1), 82-102.

[12] Plopski, A., Hirzle, T., Norouzi, N., Qian, L., Bruder, G., & Langlotz, T. (2022). The eye in extended reality: A survey on gaze interaction and eye tracking in head-worn extended reality. ACM Computing Surveys (CSUR), 55(3), 1-39.

[13] Schuetz, I., & Fiehler, K. (2022). Eye tracking in virtual reality: Vive pro eye spatial accuracy, precision, and calibration reliability. Journal of Eye Movement Research, 15(3).

[14] Bektaş, K., Strecker, J., Mayer, S., & Garcia, K. (2024). Gaze-enabled activity recognition for augmented reality feedback. Computers & Graphics, 119, 103909.

[15] Chakraborty, P., Mofizul Alam Mozumder, M., & Saif Hasan, M. (2022). Eye-Gaze-Controlled Wheelchair System with Virtual Keyboard for Disabled Person Using Raspberry Pi. In Machine Intelligence and Data Science Applications: Proceedings of MIDAS 2021 (pp. 49-61). Singapore: Springer Nature Singapore.

[16] Emile Tatinyuy, V., Noumsi Woguia, A. V., Ngono, J. M., & Fono, L. A. (2024). Multi-stage gaze-controlled virtual keyboard using eye tracking. *PloS one*, *19*(10), e0309832.

[17] Al-Kassim, Z., & Memon, Q. A. (2017). Designing a low-cost eyeball tracking keyboard for paralyzed people. *Computers & Electrical Engineering*, *58*, 20-29.

[18] Bhagat, M. S., Patil, T., Singh, V., Bhatt, A., & Mumbaikar, S. (2019). iGaze-Eye Gaze Direction Evaluation to Operate a Virtual Keyboard for Paralyzed People. *Int. Res. J. Eng. Technol.*, 51-55.

[19] Cecotti, H. (2016). A multimodal gaze-controlled virtual keyboard. *IEEE Transactions on Human-Machine Systems*, *46*(4), 601-606.

[20] Chakraborty, P., Roy, D., Rahman, M. Z., & Rahman, S. (2019). Eye gaze controlled virtual keyboard. *International Journal of Recent Technology and Engineering*, *8*(4), 3264-3269.

[21] Bradski, G. (2000). The opencv library. *Dr. Dobb's Journal: Software Tools for the Professional Programmer*, *25*(11), 120-123.

[22] Lugaresi, C., Tang, J., Nash, H., McClanahan, C., Uboweja, E., Hays, M., ... & Grundmann, M. (2019, June). Mediapipe: A framework for perceiving and processing reality. In *Third workshop on computer vision for AR/VR at IEEE computer vision and pattern recognition (CVPR)* (Vol. 2019).

[23] MediaPipe Face Mesh, https://chuoling.github.io/mediapipe/solutions/face_mesh.html, MediaPipe, Access Time: 01.03.2025