Konya Mühendislik Bilimleri Dergisi, c. 13, s. 3, 910-926, 2025
Konya Journal of Engineering Sciences, v. 13, n. 3, 910-926, 2025
ISSN: 2667-8055 (Electronic)
DOI: 10.36306/konjes.1619363

NEW TURKISH VIRTUAL KEYBOARD APPLICATION USING SIMPLE CAMERA-MOUNTED EYEGLASSES

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Highlights

- Turkish virtual keyboard application that allows eye-typing based on an eye-tracking system
- Typing speed, accuracy, and user satisfaction of the system
- The average speed is 6.74 words/minute and an accuracy of 95.5%

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(Received: 13.01.2025; Accepted in Revised Form: 30.06.2025)

ABSTRACT: In recent years, many studies have been conducted to enable people with ALS and similar neuromuscular diseases to communicate by writing with their eyes. The methods used in the literature have various disadvantages: electrooculography-based methods involve electrical connections that come into contact with the person, infrared camera-based methods are commercial systems with high costs, and webcam-based methods have low performance. In this study, a Turkish virtual keyboard application that allows eye-typing based on an eye-tracking system created with a mini camera mounted on the frame of glasses was introduced, and its performance was tested. Experiments were conducted with 20 healthy volunteers in two sessions on different days, and typing speed, accuracy, and user satisfaction of the system were measured. In the first session, users were able to write the given pangram with an average speed of 6.19 words/minute and an accuracy of 94.1%, while in the second session, they were able to write it with an average speed of 6.74 words/minute and an accuracy of 95.5%. With the word completion feature added to the system, typing speed has increased even more. It has been evaluated that the developed system can be an alternative to commercial systems in terms of price performance.

Keywords: *Graphical User Interface, Virtual Keyboard, Eye-Typing, Human-Computer Interaction*

1. INTRODUCTION

Eye tracking is the process of following the gaze points and eye movements. Intensive studies have been conducted on eye tracking in various disciplines such as advertisement, human-computer interaction (HCI), psychology, and neuroscience, as they provide information about the cognitive and psychological state by detecting the focus of attention [1],[2]. Eye tracking technologies is used in various commercial areas. It is used for menu selection in smart TV or home automation systems, reducing accident risks by measuring drivers' attention and sleep status and for marketing purposes by determining the focus of attention [3],[4].

In patients with impaired nervous and muscular system functions, such as paralysis and Amyotrophic Lateral Sclerosis (ALS is a disease caused by the loss of motor nerve cells in the central nervous system, in the area called the spinal cord and brainstem. The loss of these cells leads to muscle weakness and wasting.), the brain usually functions properly, and the ability to move the eyes continues, even though they cannot control other muscles [3]. In recent years, the number of eye-tracking studies on patients' ability to use wheelchairs, home automation systems, and to communicate with their eyes has increased [3]-[6].

Three techniques are generally used for eye-tracking: electrooculography (EOG), video oculography (VOG), and video-based infrared (IR) tracking. EOG-based systems measure electrical potentials arising from eye movements by placing electrodes around the eyes. This method has disadvantages such as complex electronic equipment and electrodes attached around the eyes, causing discomfort to the patient. VOG is a video-based tracking method that uses simple cameras mounted on the head or positioned remotely. Although VOG systems are simple and inexpensive, their eye-tracking performance is low. Another video-based eye tracking method uses IR-based cameras based on the

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detection of the temperature of the nerve activity concentrated in the fovea from the pupil. The gaze point can be determined more precisely using these systems. Although this technology meets the need for high-performance eye tracking, the prices of these commercialized systems have reached tens of thousands of dollars. This situation limits the access of disabled individuals to this technology. For this reason, studies on eye tracking systems using simpler cameras that can be obtained at affordable prices continue over a wide range.

In their previous study, the authors showed that 23 gaze regions on a normal-sized screen could be separated from each other with remarkably high accuracy by using a webcam-based eye-tracking system mounted on glasses to reduce the effect of head movements [7]. In this study, a relevant eye-tracking system was developed by eliminating the deficiencies detected during usability tests and turning it into a virtual keyboard on which disabled individuals can type with their eyes. The proposed eye-writing method was tested on a group of non-disabled participants.

In the next section, studies in literature are examined, and in the third section, the materials and methods required for the application of the method are explained. In the fourth part of the article, the research findings are presented. In the fifth and last sections, the results are discussed and suggestions that may shed light on future studies are presented.

1.2. Related Work and Challenges

People with diseases in which control of the muscle or nervous system is impaired experience speech loss in the advanced stages of their disease, even if there is no major deterioration in brain function. Because many of these patients can maintain the ability to use their eyes, researchers have proposed various methods and systems that can enable them to communicate with their eyes.

A general summary of various eye-typing systems in the literature is presented in Table 1. The table includes studies performed using only the eyes. The methods used, the writing speed, and the writing accuracy are listed in the table. For comparison, the results of studies that reported speeds in characters per minute were converted to words per minute, considering that in such studies, five characters, including spaces, are considered a word. In order to compare the accuracies, the results of the studies whose performance given as error rate were also converted to accuracy values ((1-error)*100=accuracy%).

Electrooculography (EOG) -based eye tracking is a popular method in literature. When the eye is moved from a fully forward position to one of the electrodes placed around the eye, the retina approaches the electrode, and the cornea approaches the opposite electrode. Meanwhile, a characteristic bioelectric potential develops in the electrodes with a changing dipole rotation. It has been reported that a biopotential difference of approximately 7 μV occurs when the eye moves one degree [8]. With EOG-based eye-tracking systems, these potentials are measured in the vertical and horizontal planes, the gaze direction is determined, characters are assigned to the directions viewed, and writing is attempted. Although successful eye writing systems have been developed using EOG [6, 9-11], the presence of electrical connections in contact with the skin and the discomfort caused by electrode and cable connections limit the use of such systems.

Another commonly used method is pupil corneal reflection. In this method, infrared cameras are used to detect the heat reflected from the cornea of the eye by the pupil. With this method, the gaze point can be detected with a deviation of 1.4 degrees horizontally and 1.3 degrees vertically [12]. Various studies have been carried out with different keyboard layouts using IR-based eye trackers, and a writing speed of 46 words/min has been achieved by the dwell free-eye-trace recognition method.

Another VOG-based method uses a webcam or an ordinary camera. A point on the screen can be detected with an error of 4-7 degrees (5-8 cm) when the camera is placed 50–60 cm away from the eye. The most important reason for detection errors is that the head does not remain still and constantly moves [13].

Table 1. Eye writing systems and their performances in the literature (word per minute (WPM))

References	MATERIAL-METHOD	WPM	Accuracy
[19]	EOG-based on-screen QWERTY keyboard	2.4	-
[20]	EOG-based on-screen keyboard	3.0	95.15
[21]	EOG based on-screen QWERTY keyboard	~2.9	94.4
[11]	EOG-based Codding	13.2	100
[22]	EOG based on-screen visual keyboard	~5.5	98.42
[23]	Eyelink2 pupil + corneal reflection virtual keyboard	7.85	-
[24]	Tobii 1750 pupil + corneal reflection adjustable dwell-time	19.8	-
[25]	Tobii P10 pupil + corneal reflection dwell free-eye-trace recognition	46	100
[26]	Normal camera + IR camera pupil + corneal reflection special on-screen keyboard	4.0	88.00
[27]	Tobii REX pupil + corneal reflection Dwell free-Filteryedping	15.95	-
[28]	SMI RED pupil + corneal reflection calibration-free	3.34	-
[29]	Tobii EyeX pupil + corneal reflection eye-trace recognition	11.7	98.69
[5]	Tobii 4C pupil + corneal reflection Calibration free	1.15	97.0
[30]	Webcam On-screen keyboards GazeTalk Stargazer	6.6 3.4	Error Corrected 100
[31]	Webcam T9 text input keyboard	4.0	~97.5
[16]	Webcam on-screen QWERTY keyboard chin rest	Not measured	Not measured

A group of researchers reported that when the head is fixed with an apparatus such as a vise, the point of interest can be detected with an error of approximately 1 degree [32]-[34]. Although the error rate decreased with this method, user comfort was completely ignored. Therefore, this is not a widely preferred method. One of the important reasons for this large error is that the resolution of the eye image is quite low because the camera is far from the user.

To overcome this problem, cameras have been mounted on devices such as glasses and brought closer to the eye [35]-[40]. Zhu and Ji [41] reported that by reducing the distance between the user and the camera, a higher image resolution was achieved, and the error rate was reduced. Ultimately, the vibrations created by breathing and heartbeats in the body and the constant movement of the head to maintain balance do not allow the gaze point to be determined with the desired accuracy in VOG-based systems.

There are a few webcam-based eye-typing systems in the literature. Because the gaze location cannot be determined precisely with this method, keyboard structures have been used, where a group of letters is selected at first glance, and the desired letter is selected at second glance, by using a few points placed on the screen [28],[32]. On another keyboard called Stargazer, an approach that facilitates selection has been used by zooming in on that letter and other letters around it when looking at the letters placed around a circle. With this keyboard, misspelled characters were deleted, and a writing speed of 6.6 words/minute was achieved. Among webcam-based systems, only Liu et al.'s 2019 study attempted to use a Qwerty keyboard. They used a chin rest to limit head movement. In this study, no method was used to select the letters, but the first five words consisting of the letters that the eye wanders over were presented to the user. The presence of the desired word among these five was considered successful, and writing speed and accuracy were not measured.

In recent years, studies have emerged that use the superior performance of artificial intelligence (AI) in object recognition for the purpose of typing by eye [25],[29]-[31]. Most of these studies used web cams and as can be seen in Table 1, performance levels comparable to infrared-based commercial systems have been achieved [25],[29]-[31].

2. MATERIAL AND METHODS

In this study, improvements were made to the previously developed [7] webcam-based eye-tracking system mounted on glasses. Then an eye typing system was created with the virtual keyboard developed using this system. Subsequently, studies were conducted to determine system performance.

2.1. Developed Eye Tracking System

The webcam-based eye-tracking system that we developed previously uses the iris center coordinates obtained from the real-time image captured with the camera using a Hough transform-based method to determine the gaze point.

The current gaze point was determined by classifying it using the k-nearest neighbor algorithm, according to the gaze points learned during the calibration phase. This eye-tracking system was tested on 20 users and was found to be able to detect 23 points on a screen with 99.54% accuracy [7].

In the previously developed system, a 2.5 cm*2.5 cm webcam was mounted on a plastic glasses frame approximately 8 cm away from the eye, aligned to the center of the eye. In this system, although all points on the screen could be seen from a distance of 60 cm when gazed at with two eyes, the size of the camera limited the field of view. For this reason, low cost (below 25$), a borescope type camera with a very small size and weight (0.28 cm in diameter) was used for this study. Figure 1 shows the glass-mounted camera system used in this study.

Figure 1. Glass-mounted camera system

2.2. Developed Virtual Keyboard

In our previous study, it was observed that there should be at least 8 cm distance between the points chosen by the eye in order to detect them without confusion. Considering this situation, 23 gaze points were placed on a screen measuring 49 × 27 cm. However, the Turkish virtual keyboard (Figure 3) developed for this study requires 29 letters, one space, and several command entries. That's why 2 letters have been placed in some of these spots on the screen. When looking at a point, the first character here is activated through the software. If the eye is held at this point for more than 0.5 seconds, the second letter at the same point becomes active. The active character is turned red via the software and the user is notified. After 0.5 seconds, the other letter in the same position becomes active again, and so on. If a letter is missed, it can be reached again by keeping the eye at the same point for more than 0.5 seconds. While the letters were placed on the screen, the letter usage frequencies in Turkish literature in figure 2 were taken as reference [42]. The five letters with the highest usage frequency (A, E, İ, N, R) were placed in the first selectable positions closest to the center of the screen (Figure 3). Considering that there will be a space between words approximately every five characters, the point just to the right of the center is reserved for the space character. The other 11 characters in the most used letters list were placed in the first selectable position in second-degree proximity to the center. The point on the far left of the screen, indicated by the (<) symbol, was designated as the command entry to delete the last written letter. While placing the remaining characters, to make it easier to remember the location of the letters, vowel and consonant letters with similar appearance and sounds (O and Ö, U and Ü, S, and Ş) were assigned as the characters to be chosen in the second row behind the letter they resemble. Other characters were assigned as second-position characters, starting from five points near the center. The most frequently used punctuation marks (full stop, comma, and question mark) were also placed at points away from the center.

A → 11.82	I → 5.12	T → 3.27	Z → 1.51	C → 0.97
E → 9.00	K → 4.70	S → 3.03	G → 1.32	Ö → 0.86
İ → 8.34	D → 4.63	B → 2.76	Ç → 1.19	P → 0.84
N → 7.29	M → 3.71	O → 2.47	H → 1.11	F → 0.43
R → 6.98	Y → 3.42	Ü → 1.97	Ğ → 1.07	J → 0.03
L → 6.07	U → 3.29	Ş → 1.83	V → 1.00	

Figure 2. Usage frequencies of letters in the Turkish Alphabet[42]

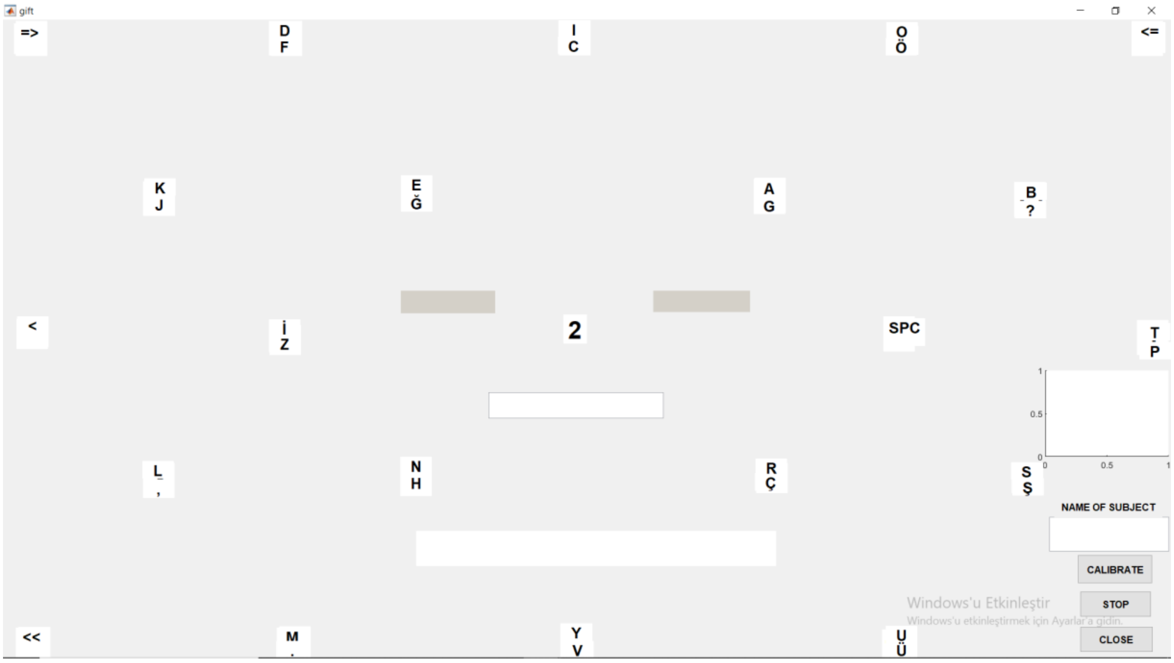

Figure 3. Designed virtual keyboard

Various strategies have been used to select letters intended to be written on virtual keyboards developed for eye typing. In many studies, dwell time has been used to select characters. As can be seen from Majaranta et al. [43], dwell time is one of the most important parameters that determines writing speed. It has been observed that when the dwell time is shortened, typing speed can be increased to approximately 20 words/min. In another group of studies, voluntary eyeblinks were used to confirm the selected character [10],[15],[28]. However involuntary blinking may result in incorrectly written characters [10]. Excessive blinking can lead to dryness and fatigue [15].

In this study, the midpoint of a screen (numbered with 2 in Figure 3) was used to confirm the selection of letters. When the user looks at a letter, it is turned red by the software, and it is understood that it is ready for writing. The letter was then confirmed by looking at the center point of the screen. The approved letter was written in the edit box immediately just below the center point. When the user looks at the space character (SPC) to indicate the completion of the word, the word in this box is transferred to the lower window, where all the written text is stored. A miniature image of the virtual keyboard was added around the checkpoint in the middle of the screen to help users find the location of the letters more easily.

Shortcuts to choose one of the two most used words, starting with letters typed on the virtual keyboard, were also added. The two most used words that start with the letter that begins to be typed are seen in the text boxes on the top-right and top-left of the reminder keyboard. To confirm them, the user can select these words and transfer them to the typing box by looking at the upper left and upper right corners of the keyboard, indicated by the “=>” and “<=” symbols. The "<<" character, which symbolizes deleting the entire last written word, was placed in the lower right corner of the screen, and the lower left corner was not used because it was the point where the most detection mistakes were made during our development process. In the space on the right side of the keyboard, a text box for entering user information, a monitoring window to instantly monitor whether the iris circle was detected correctly, and buttons to start the calibration, stop the operation, and close it, were placed.

2.3. Used Hardware

A borescope-type camera (HD810, Powermaster, China) that can capture images at 30 fps with 640 ×

480 and 320 × 240 resolution options was used in this study. The diameter of the camera is 0.28 cm. The camera was mounted on a plastic eyeglass and positioned 5 cm away from the frame, centered on the center of the left eye. The image taken from the camera was transferred to the computer via the USB port, and the image was captured in real-time (every 100 ms) and converted into text using a program written in MATLAB 2022a (The MathWorks Inc., Natick, USA) program development environment. During the experiments, a laptop with 16 GB RAM, an Intel Core i7 (3.3 GHz) processor running the Windows 10 operating system, and a 22-inch monitor with 1620 × 1080 resolution were used.

2.4. Tests

To determine the performance of the newly developed eye-typing system, subjects are usually asked to write a text, and their writing speed and accuracy are measured. Although participants were required to write whatever they wanted in accordance with their normal usage, this created difficulties in comparison. In the literature, participants are generally asked to write predetermined test texts. When creating the word set to be used as the test text, care should be taken to ensure that it is easy to remember and represent the target language [44]. To measure the performance of the designed system, we focused on determining a set of words that contain all 29 letters of the Turkish alphabet at least once, and whose usage frequency matches the frequency of letter usage in Turkish literature. For this purpose, it was decided to use the most well-known Turkish pangram, which includes all the letters of the Turkish alphabet and is memorable, as "PİJAMALI HASTA YAĞIZ ŞOFÖRE ÇABUCAK GÜVENDİ." [45]. The usage rate of the first six most frequently used letters in Turkish (A, E, İ, N, R, L) was 49.5% [42]. In order to reflect this ratio in the pangram sentence, the word "ŞOFÖRE" was made plural and changed to "ŞOFÖRLERE".

2.4. Participants

Participants were selected from among people who had no knowledge or experience of typing with their eyes. Permission to conduct the non-disabled human experiments was obtained from the Başkent University Clinical Research Ethics Committee. Before the experiments, signed statements were obtained from the participants, stating that they voluntarily participated in the experiment. Twenty subjects, 8 men and 12 women participated in the experiments. The average age of the subjects, who were university students and academics, was 25.95 (20-49).

2.5. Experimental Environment

An image of the experimental setup is shown in Figure 4. Users were asked to sit comfortably in front of the screen at a 60 cm distance with support from a table. The height of the screen was adjusted such that the center point on the virtual keyboard was directly opposite to the eye with the camera attached during the experiments. The users were asked to align the camera in the middle of the screen without moving their heads. The experiments were carried out under fluorescent lighting with closed curtains because fluctuations in ambient light make iris detection difficult. The lighting level of the environment was measured between 190-250 lumens by using a Voltcraft MS-1300 lux meter. The light level of the user screen was set to 80 lumens, and care was taken to ensure that there were no light changes in the experimental environment.

Ideally, a 10-day testing procedure should be planned to determine the typing learning curve of the user. The eye-writing speed in previous studies did not exceed a few words/minute. It was thought that the experimental period, which could be very long, would make it difficult to find subjects to continue for 10 sessions. For this reason, it was decided that it would be more appropriate to organize two sessions in which the selected pangram was written five times in each.

Figure 4. Experimental environment

In the first session, the developed system was introduced to the participants, and a 10-minute practical training session was provided. They were then asked to write words of their own choice for five minutes to familiarize themselves with the system. Before starting the experiments, each participant underwent a calibration procedure lasting approximately 60 seconds, in which they looked at all points on the keyboard with the visual and auditory guidance of the software. After the subjects were warned with a bing sound, they were directed to gaze at the letter blocks by turning red, and they were asked to follow these points only with eye movement, without moving their head.

The users were asked to write words in the pangram five times each during the experiment. Thus, the users wrote 235 (47 × 5) characters (30 words), including spaces, in one session. Participants were asked to try to type as fast as possible and not correct possible spelling errors, even though this was possible on the virtual keyboard. Finally, the participants were asked to write the pangram five more times using the word completion feature.

Subjects who attended the first session were invited to the second session with at least a one-day break. All the subjects who attended the first session volunteered to participate in the second session. In second session, the introduction and training stages were skipped, and participants were asked to write the pangram sentence five more times, with and without using word completion, according to the same procedure. At the end of the experiment, users filled out the small survey shown in Table 2, in which they expressed their opinions and suggestions regarding the usability of the system. In the survey, participants were asked to indicate their degree of satisfaction with the system and method (1= Strongly disagree, 2= Disagree, 3= Neutral, 4= Agree, 5= Strongly agree).

Table 2. A survey was administered to participants

No	Question
1	Calibration was easy.
2	The typing procedure was easy to learn
3	It was easy to find letters on the keyboard.
4	It was easy to confirm the chosen letter.
5	I enjoyed the gaze-based typing experience.
6	I would recommend others to participate in the experiment.
7	I can write faster if I practice more.

2.4. Used Metrics and Computational Tools

The writing speed and accuracy metrics in the literature were used to measure the performance of the developed system. To determine the writing speed, five characters, including spaces, were accepted as a word in accordance with the literature in the field [46],[47]. The writing speed was expressed in words/minute for each word separately and for the entire sentence. While the error rate has been reported in some eye-typing studies, accuracy (correct writing rate) has been reported in other studies. Accuracy was preferred in this study and was calculated as the ratio of the number of correctly coded characters to the total number of characters for words separately and for the entire pangram.
Student's t-test was used to investigate whether there was a statistically significant change in the metrics between the first and second experimental sessions. P values below 0.05 were considered as a significant difference between the two experimental sessions.

3. RESULTS AND DISCUSSION

The average, minimum, and maximum typing speeds of the users for each word and the entire pangram, are given in Table 3. Statistical differences between the two sessions, are marked with an asterisk (" * "). It was observed that users could write the entire pangram at an average speed of 6.19 words/minute in the first session and 6.74 words/minute in the second session. The writing speed increased in the second session and significant differences were found between the two sessions for most words and all pangrams ($p<0.0005$). Although there was a small increase in typing speed for the word "PİJAMALI", no statistically significant difference was observed. For the entire sentence, the maximum typing speed could reach up to 9.68 words/minute, while the minimum typing speed could drop to 3.19 words/minute. According to the averages, the fastest written word in both sessions was "HASTA" with 7.23 and 7.88 words/minute, and the slowest was "GÜVENDİ" with 5.5 and 5.92 words/minute. While the highest individual writing speed was reached in the word "PİJAMALI" with 12.15 words/minute, the slowest written word was "ÇABUCAK" with 2.4 words/minute.

Table 3. Typing speeds in two sessions (WPM)

	Mean		Max		Min	
Words	Session1	Session2	Session1	Session2	Session1	Session2
PİJAMALI	6.40	6.72	12.15	10.42	3.20	3.04
HASTA	7.23	7.88**	10.62	10.17	3.08	4.29
YAĞIZ	5.89	6.46**	9.66	8.37	3.41	2.7
ŞOFÖRLERE	6.12	6.72**	8.82	8.71	3.71	4.2
ÇABUCAK	5.95	6.71**	8.67	9.33	2.58	2.4
GÜVENDİ	5.55	5.92*	8.14	9.09	3.19	3.11
ALL PANGRAM	6.19	6.74**	9.68	9.35	3.19	3.3

* : $p<0.05$, ** : $p<0.001$

When the placement of the letters of "HASTA", which is the fastest written word according to the average, is examined on the keyboard (Figure 3), it is seen that only "H" is the second letter that can be selected after waiting for a while, and the others are in positions that can be selected at first glance. It can be determined that the 3 letters in "GÜVENDİ", which can be written the slowest according to the averages, are the letters that come in second place and can be selected by waiting for a while.

The users' average, minimum, and maximum writing accuracies for each word and the entire pangram, and those with a statistical difference between the two sessions, are marked with an asterisk (" * ") and are given in Table 4. It was observed that users could write the entire pangram with an average accuracy of 94.4% in the first session and 95.5% in the second session. However, there was a significant difference ($p < 0.05$) only for the word "PİJAMALI" between the two sessions. From the maximum columns in the table, it can be seen that at least one of the subjects could write the entire sentence without any errors in both sessions. When writing the entire sentence, a lower accuracy was achieved in the first session (81.2 %). When evaluated on a word basis, it was seen that the word that could be written with the highest accuracy in both sessions was "HASTA" with 95.6% and 97%. According to the averages, in the first session, the words that could be written with the lowest accuracy were "PİJAMALI" and "ŞOFÖRLERE" with 92.2%, and in the second session, the words "GÜVENDİ" with 93.7%. When looked at on an individual basis, the lowest writing accuracy was seen in the word "YAĞIZ" with 74.7%.

Table 4. Writing accuracies (%) in two sessions

	Mean		**Min.**		**Max**	
Words	Session1	Session2	Session1	Session2	Session1	Session2
PİJAMALI	92.2	95.4*	82.5	86.7	100	100
HASTA	95.6	97	82	89.3	100	100
YAĞIZ	92.9	94.6	74.7	85	100	100
ŞOFÖRLERE	92.2	96	87.6	88.9	100	100
ÇABUCAK	94.9	96.1	80	86.8	100	100
GÜVENDİ	94.7	93.7	80.4	86.1	100	100
ALL PANGRAM	94.4	95.5	81.2	87.1	100	100

* : $p<0.05$, ** : $p<0.001$

The results of the writing experiments, performed using word completion, are presented in Table 5. According to the averages, the entire sentence could be written with 22.96 words/minute in the first session, while it could be written with 25.88 words/minute in the second session. It was observed that the typing speeds of the subjects increased in the second session. Significant differences (smaller for the whole pangram ($p<0.05$) and larger for some words ($p<0.001$)) were seen between the two sessions. When the words are considered, the highest writing speed according to the averages was reached in the word "ŞOFÖRLERE", which consists of the most letters, with 33.13 words/minute. The subject who wrote the fastest was able to write this word in 49 words/min.

Table 5. Typing speeds achieved with the word completion feature

	Mean		**Max**		**Min**	
WORDS	Session1	Session2	Session1	Session2	Session1	Session2
PİJAMALI	23.92	30.07**	34.09	38.82	12.88	23.24
HASTA	16	19.62**	21.97	25.96	7.96	12.87
YAĞIZ	16.86	20.10*	23.35	30.36	10.8	5.84
ŞOFÖRLERE	31.69	33.13	42.8	49	7.3	5.70
ÇABUCAK	25.74	25.98	41.28	40.25	6	4.9
GÜVENDİ	23.57	26.35*	35.97	36.52	6.25	6.25
ALL PANGRAM	22.96	25.88*	33	37	8.5	9.8

* : $p<0.05$, ** : $p<0.001$

The results of all experiments were graphed to see the effect of users getting used to the eye-writing method and system on writing speed and accuracy. Figures 5 and 6 show the changes in average typing speed and accuracy in the first and second sessions according to the number of repetitions, respectively. According to Figure 5, typing speed generally tends to increase with number of repetitions within and between sessions. As seen in Figure 6, although there were fluctuations in the writing accuracy of some words during the sessions, a general increase was observed in the second session.

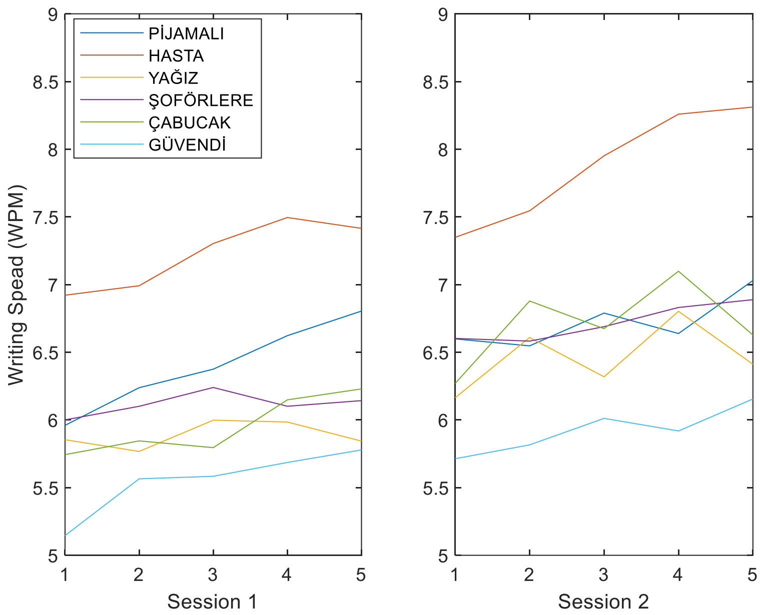

Figure 5. Variation of writing speed according to the number of repetitions.

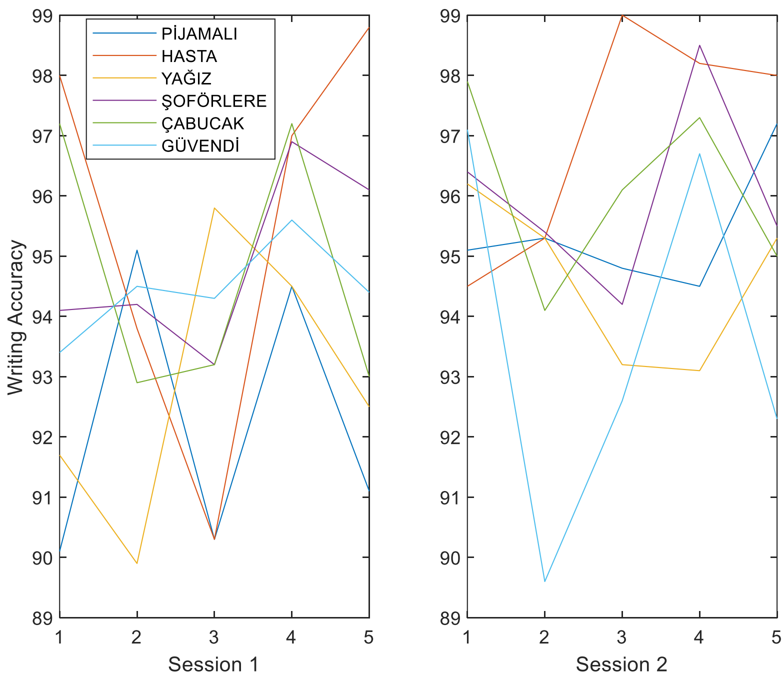

Figure 6. Variation of error rate according to the number of repetitions.

The results of the user experience survey applied to the subjects are presented in Table 6. According to the table, the highest approval was for the proposition " I can write faster if I practice more " with 4.9, and the lowest approval was for the proposition "It was easy to find the letters on the keyboard" with 3.85.

Table 6. User experience survey results

No	Question	Result
1	Calibration was easy.	4.40
2	The typing procedure was easy to learn.	4.30
3	It was easy to find letters on the keyboard.	3.85
4	It was easy to confirm the chosen letter.	4.55
5	I enjoyed the gaze-based typing experience.	4.65
6	I would recommend others to participate in the experiment.	4.85
7	I can write faster if I practice more.	4.90

The maximum value of the scale is 5.

4. CONCLUSIONS

In this study, a simple eye tracking system was developed using a mini camera mounted on glasses that can be used by people with neuromuscular diseases who may need to write with their eyes. Then, the performance of the eye writing method using this system was measured. A pangram sentence containing all the letters in Turkish at least once was written with the eyes of 20 healthy users five times in two different sessions, and the performance of the system was determined according to the results of these experiments.

In the first session, users were able to write the given pangram with an average speed of 6.19 words/minute and an accuracy of 94.1%, while in the second session, they were able to write it with an average speed of 6.74 words/minute and an accuracy of 95.5%. Considering the statistical difference between the two sessions in the two metrics and their changes in graphs with the number of repetitions (Figure 5, Figure 6), it can be said that as familiarity with the eye-writing system increased, writing speed and accuracy increased.

During the experiments, the maximum writing speed reached for the entire pangram sentence was 9.68 words/minute, and the minimum writing speed was 3.19 words/minute. It has been observed that in trials where the typing speed is very low, users realize that they have typed incorrectly and seek to correct this. These subjects caused the average typing speed to be lower than it could have been. Because the experimental procedures took a long time, the number of experimental sessions was limited to two. If the number of experiments is increased, it is estimated that the average writing speed will converge to the maximum writing speed in the experiments with familiarity.

When the feature added to the system to suggest the most used words starting with the written letter and to select the suggested words in shortcuts was used for the words in the pangram, the average writing speed reached 25.88 words/minute. Since all the words in the pangram were used frequently during the trials, they became visible when their first letters were written. In real use, a word to be written can be seen after more than one letter. In this case, the speed achieved during the experiments might not have been reached. Nevertheless, word completion is likely to lead to a significant increase in typing speed.

The average typing speed (6.74 words/minute) achieved in the application where all characters were written one by one was higher than the 5.58 words/minute achieved with the highest speed EOG-based writing system tested with a large group [48]. Yildiz and Ülkütaş [9] reached a writing speed of 13.2 words/minute with a single expert subject with the EOG-based system they developed. In our study, the subject who reached the highest writing speed in the trial in which all letters were coded one by one was able to write 9.68 words/minute, falling behind the speed achieved by Yildiz and Ülkütaş [9]. However, it was observed that this speed can be exceeded by using the word completion feature in our system. The developed camera-based system also eliminates the problems of EOG-based systems, such as the discomfort caused by electrical cables in contact with the user, and the complexity of the electronic system. As a result, it has been evaluated that the method proposed in this study can be preferred over EOG-based systems.

When we look at the performance of eye writing systems using pupil corneal reflection-based commercial systems in Table 1, it can be seen that they have writing speeds between 1.15 words/minute and 46 words/minute, and accuracies between 88% and 100%. When writing was performed by coding all letters one by one using the method developed in this study, the writing speed and accuracy fell behind some of the mentioned systems. When shortcuts are used, it can be said that a higher typing speed is achieved than many studies in literature. However, it should be noted that since all the words in the pangram used in the experiments were written using shortcuts, our results will not show the real performance of using shortcuts.

In commercial systems where writing speed and accuracy are high, the gaze point is found by pupil-cornea reflection, so it can be detected more precisely, and all characters in the alphabet used can be placed at separate points on the screen. In addition, the image acquisition and processing speeds were higher than those of the current eye tracking system. With improvements in the performance of the eye-tracking system, it may be possible to reach the typing speed and accuracy levels achieved by commercial systems. Considering that commercial eye-tracking systems worth several thousand dollars were used in the aforementioned studies, it can be said that an affordable eye-typing system was achieved with very good performance in accordance with the purpose of the study. It may even exceed the performance of some eye-writing systems with the word completion feature.

In studies using simple cameras similar to ours, writing speeds between 3.4 and 6.6 words/minute were possible. The average typing speed we achieved was 6.74 words/minute is even higher than the fastest of these. This difference can be further widened by adding a word completion feature.

Owing to the low performance of the eye-tracking system, which was implemented using a simple camera, two characters were placed at the entry points on the screen. The word "HASTA", consisting mostly of letters placed in the first row, could be written at speeds above 10 words/minute. This shows that, if the performance of the eye-tracking system is increased and all characters are encoded with a single glance, the typing speed of the system can increase.

In this study, writing systems that use only the eyes are discussed. There are also studies in which characters are followed by the eye and selected using various body parts [49][50]. Mifsud et al. used EOG to find the character being looked at and click on the touch screen for confirmation. The typing speed achieved was 12.85 words/minute. Meena et al. found the looked location with a pupil corneal reflection-based eye tracking system and selected the letters using the Myo armband (Thalmic Labs Inc., Canada) and soft-switch (The QuizWorks Company, USA). In their study, a writing speed of 21.83 words/minute was achieved.

As can be seen from Table 1, this study focused on eye typing systems. In addition, our study can be compared with EEG-based systems that enable communication among disabled individuals. In pioneering studies conducted with EEG, the writing speed does not exceed a few characters per minute [51]. As a result of the improvements made, the highest speed that can be achieved in EEG-based studies is approximately 12 words per minute [52]. The developed system is slower than the fastest EEG-based systems when letters are written one by one, but faster when the word completion feature is activated.

The given pangram sentence could be written with an average accuracy of 95.5% in the second session. When the misspelled characters were examined, it was determined that the errors mostly occurred when selecting one of the two characters placed at the same point. To avoid this problem, the transition time from one character to another can be slightly extended. However, this may slightly reduce the typing speed. Letter writing accuracy increased by 1.4% in the second session compared to the first session. It can be considered that as user experience increases, error rates will decrease further. It was observed that the participants who participated in the usage experience survey thought that the developed system was easy to use and that they could write faster as their experience increased. It was easy to find letters on the keyboard" option received the lowest score (3.85) in the satisfaction survey. It was understood that the subjects had difficulty finding the location of letters on the keyboard.

In the future, after obtaining the necessary ethics committee approval, the system should be tested on disabled individuals. The experiments can be repeated by increasing the participant groups, sessions, and the intervals between sessions. In addition, the system can be tested for different age groups. Developing algorithms to compensate for head movements and placing a keyboard on the screen that allows all characters to be selected with a single gaze could significantly increase typing speed.

As a result, the developed system can be an alternative to commercial systems in terms of price performance. Patients who need visual communication can have the introduced system without incurring a large economic burden.

Declaration of Ethical Standards

The authors declare that all ethical guidelines including authorship, citation, data reporting, and publishing original research. Permission to conduct the human experiments was obtained from the Başkent University Clinical Research Ethics Committee.

Credit Authorship Contribution Statement

Providing information to participants, conducting participant tests, collecting data, and writing the original draft was performed by Seval UĞURLU. Muhammet YORULMAZ performed experimental design, writing, reviewing, and editing. Finding the idea, designing the experiment, conducting analyses, writing, and reviewing were performed by Metin YILDIZ.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding / Acknowledgements

The authors declares that there is no financial support.

Data Availability

Data in the study will be made available by the authors upon reasonable request.

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