A feasibility study of an eye-writing system based on electro-oculography

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A Feasibility Study of an Eye-writing System Based on Electro-oculography

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Abstract

Eye-writing herein introduced is a novel language communication method wherein the eyes fill the role of a writing organ. An eye-writing system detects the traces of eye movements and determines their corresponding symbols by pattern recognition. In this study, we measured the eye movements by electro-oculograaphy (EOG). The electrical potential difference measured between the skins above and below the eyes reflected the eye movement in the vertical direction. That measured between the skins to the left and to the right of the eyes reflected the eye movement in the horizontal direction. We evaluated the eye-writing system with a symbol set consisting of symbols of 10 Arabic numerals and 4 mathematic operators. Experiments on 11 voluntary human subjects showed recognition rate ranging from 50% to 100 % with different symbols. The recognition rate can be improved by several means to reach a desired level for practical applications. We conclude that eye-writing as a language communication method is feasible. This technology will be especially useful for severe amyotrophic lateral sclerosis (ALS) patients who have lost the oral-speaking and hand-writing abilities.

Keywords: Amyotrophic lateral sclerosis, Electro-oculography, Eye, Writing

1. Introduction

The electrical model of the eye ball is a dipole that is relatively positive on the corneal side and relatively negative on the retinal side [1]. The movement of the eyes manifests itself as electrical potential changes on the skin around the eyes. Electro-oculography (EOG), which measures the potential difference in the electrodes attached to the skin around the eyes, has been found valuable in various clinical applications. It can assist in the evaluation of eye injuries [2], the diagnosis of eye diseases [3], and the study of Parkinson's disease [4], Alzheimer's disease [5], psychological disorder [6], sleep patterns [7], etc. It is also useful in the human-machine interface in systems such as an eye-controlled wheelchair [8-9], an eye-controlled robot [10], etc. Other applications include using the EOG signal of the normal eye to control the motion of the prosthetic eye for a person who has lost one eye [11].

Utilizing EOG, this study aimed to develop an eye-writing system that recognizes the symbols that the user 'writes' by moving the eyes to trace the paths of predefined stroke patterns. The system was designed primarily to facilitate the communication of those amyotrophic lateral sclerosis (ALS) patients who have lost their oral speaking and handwriting abilities. ALS is a disease resulting from the degeneration of the lower motor neurons in the spinal cord and in the brain stem and the upper motor neurons in the brain [12]. It attacks the muscles responsible for limb functions, speaking, swallowing, and breathing. Characterized by progressive weakness of the muscle functions, ALS patients gradually lose their abilities to move and may become totally paralyzed in the later stages of the disease. However, the sensory neurons are not affected. Patients still have normal vision, hearing, smelling, and tactility. The eye muscles are generally not affected and become the last resort for communication as the disease progresses further.

Various communication methods based on eye movements have been utilized or published. Caregivers have long been using a board with symbols, letters, words, or even sentences on it to help the ALS patients express what they want to say. The caregiver points to the items on the board one by one and the patient chooses the target items by the eye blinking. It is desired to instrument this primitive type of communication. Yano *et al.* proposed an image processing method to detect the opening and closing of the eyelids from the facial images captured with a video camera [13]. Tomita *et al.* designed a system in which the cursor movement on a computer screen could be controlled with the user's EOG signals. The user double blinked the eyes to select a specific

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letter pointed to by the cursor [14]. In a system designed by Tecce *et al.*, the user selected a character displayed on a computer screen by using his or her eyes to control the cursor to move to and stay in the bin that contained the character. The computer calculated the cursor position based on the waveforms of the horizontal and vertical EOG signals. A character was selected if the cursor remained in a bin for longer than a specified length of time [15]. Maehara *et al.* developed a system that calculated the relative position between the iris and the eyebrow from the image taken from a patient who was gazing at an area on a computer screen. The information was used to detect the area gazed at by the patient. The computer screen in the system contained 12 divided areas, each representing a potential intention of the patient [16]. Beside EOG, electroencephalography (EEG) has also been used to facilitate the communication through the eyes [17-18]. Although usable, these systems all relied on a display screen to show the letters or words for the user to select.

The eye-writing method introduced in this paper dispenses with the use of a display. In this research, we defined a symbol set to evaluate the feasibility of the eye-writing system. Electo-oculograms were acquired from voluntary human subjects while they were eye-writing the symbols. A computer processed these EOG signals and recognized them as the elements of the symbol set. This paper reports the performance of the system in terms of symbol recognition rates.

2. Method

2.1 Symbol set

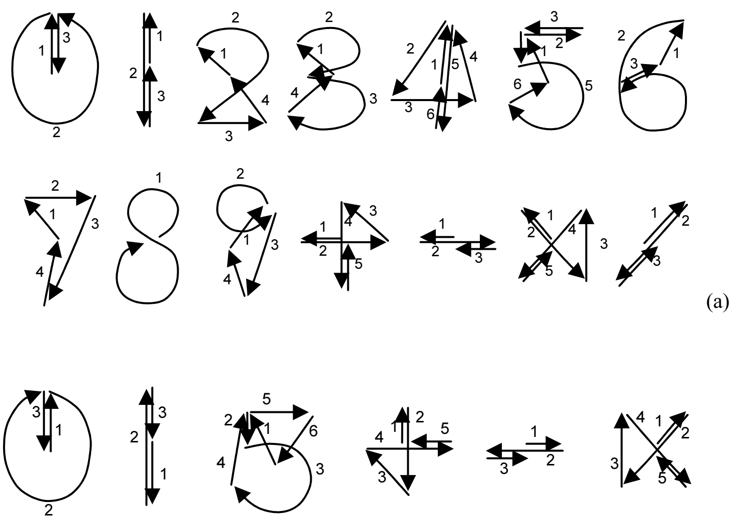
The symbol set we defined to evaluate the eye-writing system consisted of 10 Arabic numerals and 4 mathematic operation symbols:

$$S = \{‘0’, ‘1’, ‘2’, ‘3’, ‘4’, ‘5’, ‘6’, ‘7’, ‘8’, ‘9’, ‘+’, ‘−’, ‘\times’, ‘/’\}. \quad (1)$$

Figure 1(a) shows the predefined eye-writing trace of each symbol. Symbols ‘0’, ‘1’, ‘5’, ‘+’, and ‘×’ have alternative traces, designated ‘0_a’, ‘1_a’, ‘5_a’, ‘$+_a$’, and ‘$\times_a$’, respectively, as shown in Fig. 1(b).

2.2 Subjects and hardware

Eleven voluntary human subjects were recruited from a university campus. They were all males aged from 20 to 28 years. Five adhesive electrodes were attached to the skin around the subject's eyes during testing, as shown in Fig. 2. Electrode E_G on the upper forehead served as the indifferent electrode. Electrodes E_A and E_B attached above and below, respectively, the left eye measured the eye movement in the vertical direction. Electrode E_L attached to the left of the left eye and electrode E_R to the right of the right eye measured the eye movement in the horizontal direction. Each subject was instructed to eye-write every symbol 5 times according to the symbol traces shown in Fig. 1. The measured EOG signal reflected the relative positions between the eyeballs and the electrodes around the eyes, no matter how the head moved. Hence, the system allowed the subjects to freely move their heads or any other part of their bodies as well as to keep their eyes closed during eye-writing. However, all the subjects naturally remained motionless except moving their eyes and they all wrote with their eyes open. While the subject was eye-writing each symbol, the system recorded the time courses of the potential difference between electrodes E_A and E_B and that between E_L and E_R through voltage amplification circuits whose gains were about 900. The analog signals were then converted into 1000-sample-per-second digital signals and received by the computer, as shown in Fig. 2. Two INA128 differential amplifiers (National Semiconductor Corp., Santa Clara, California, USA) constituted the amplification circuits, one INA128 for the vertical and the other for the horizontal signal. The data acquisition device was a DAQPad 6020E (National Instruments Corp., Austin, Texas, USA) with 12-bit resolution. For instance, Fig. 3 shows the waveforms of the two recorded potential differences corresponding to symbol ‘0’ from one of the subjects. Note that there were baseline drifting and noise in both signals before further processing.



(a)

(b)

Figure 1. (a) Standard symbol traces defined for the eye-writing system. The symbols shown include ‘0’, ‘1’, ‘2’, ‘3’, ‘4’, ‘5’, ‘6’, ‘7’, ‘8’, ‘9’, ‘+’, ‘−’, ‘×’, and ‘/’. All symbol traces start and end at the center of vision. The little number alongside each segment indicates its stroke order in eye-writing the symbol. (b) Alternative traces, designated ‘0_a’, ‘1_a’, ‘5_a’, ‘$+_a$’, ‘$-_a$’, and ‘$\times_a$’.

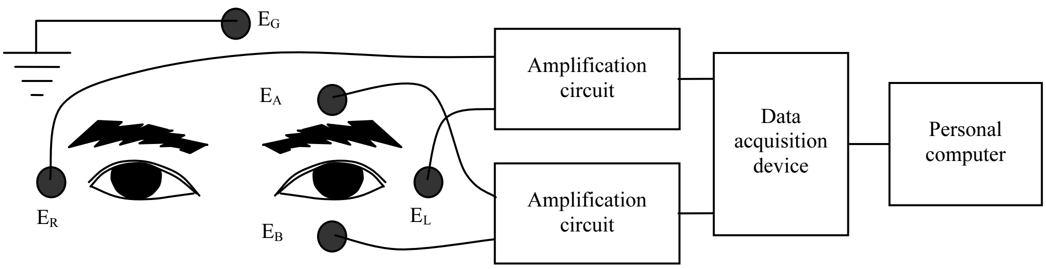


Figure 2. The hardware architecture and electrode placement of the eye-writing system. Electrode E_G attached to the upper forehead was an indifferent electrode. Electrode pairs E_A–E_B and E_R–E_L sensed the electrical potential difference arising while the eyes moved. The potential differences were converted into two digital signals by the data acquisition device after proper amplification in their amplitudes. The personal computer analyzed the digital signals to recognize the symbol that was eye-written by the user.

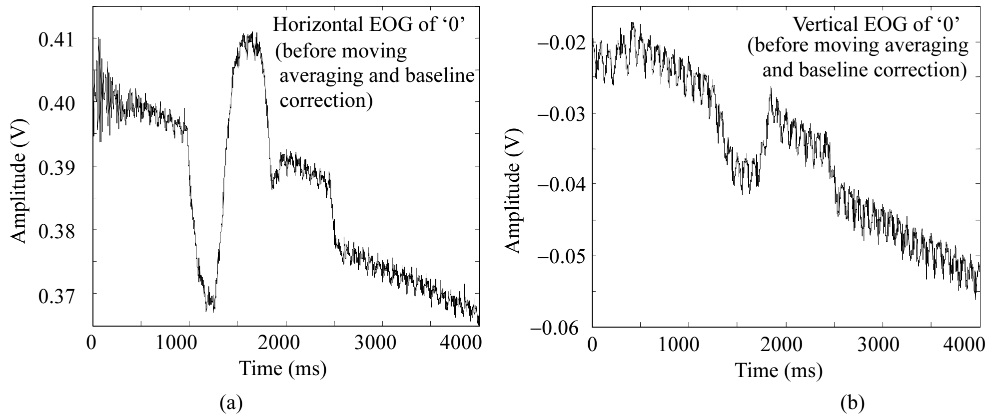


Figure 3. The amplified EOG signal acquired by the data acquisition device while the subject was eye-writing symbol '0'. (a) The horizontal EOG signal. (b) The vertical EOG signal.

2.3 Symbol recognition

The recognition of an eye-written symbol was based on the similarity between the measured EOG waveform and the standard EOG waveform corresponding to that symbol. It is worth noting that the eye-writing process was a somewhat nonlinear transformation on the symbol traces. The real traces of a human subject's eye movement could not be accurately reconstructed from the measured EOG signals through a linear mapping. Nevertheless, it was not necessary to reconstruct the real eye-movement traces, since they would not be used in the symbol recognition.

Matlab (The MathWorks Inc., Natick, Massachusetts, USA) was used to process the digital signals. A Matlab program recognized an eye-written symbol through the following steps:

1) Suppressing high-frequency interference and noise: The highest frequency of a genuine EOG signal is around 3-5 Hz. However, high-frequency noise, 60 Hz power-line interference especially, was found in the recorded signals. A moving-average filtering whose filter length was 300 samples effectively attenuated the high-frequency noise. Figure 4(a) shows the moving-averaged waveform of the horizontal EOG signal of symbol '0' shown in Fig. 3(a).

2) Correcting the baseline drift: Lengthy attachment of the adhesive electrodes to the skin brought about baseline drift on the recorded EOG signals. The baseline drift was slower than the eye movement. It manifested itself as a rising or declining slope in the EOG waveform. The system estimated the trend of the baseline drift by forming an imaginary slope that connecting the average of the first 5 samples and that of the last 5 samples of an EOG signal of an eye-written symbol. The imaginary slope was then deducted from the original recorded EOG signal to correct the baseline drift. The fact that the trace of every eye-written symbol started at and ended at the center of vision justified this method to correct baseline drift. Figure 4(b) is an example of the baseline drift-corrected waveform.

3) Cancelling exposed crosstalk: A large eye movement in the horizontal or vertical direction might cause noticeable crosstalk in the EOG signal in the other direction. Figures 5(a) and (b) show a typical case where crosstalk occurred and could be identified. So-called exposed crosstalk pulses are those low-amplitude pulses that were discernible from ordinary eye-movement signals based on an amplitude threshold. The effect of exposed crosstalk pulses was a fake turn count in the next step when the system performed classification. The system thus dealt with this problem by ignoring the turns caused by the exposed crosstalk pulses when counting the horizontal turn count or the vertical turn count, whose definitions are described immediately below. Unexposed crosstalk was not taken care of since it merged with genuine eye-writing waveform and thus had no effect on symbol recognition. A case of unexposed crosstalk is shown in Figures 5(c) and (d).

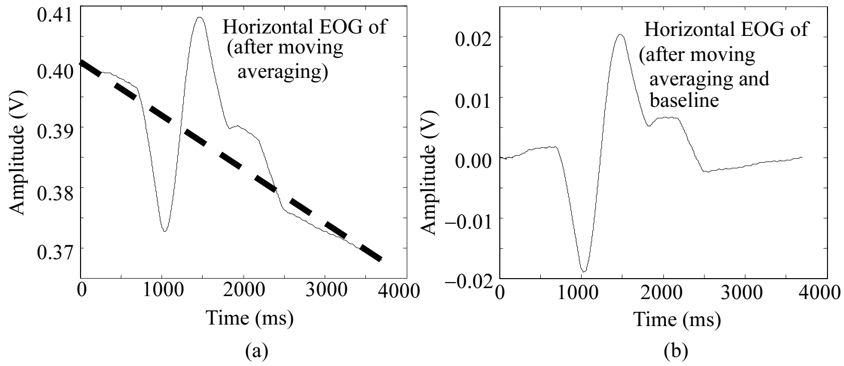


Figure 4. (a) The waveform of the horizontal EOG signal of ‘0’ after 300-sample moving-average filtering. The dashed line estimated the baseline drift. (b) The EOG waveform after the estimated baseline drift was deducted.

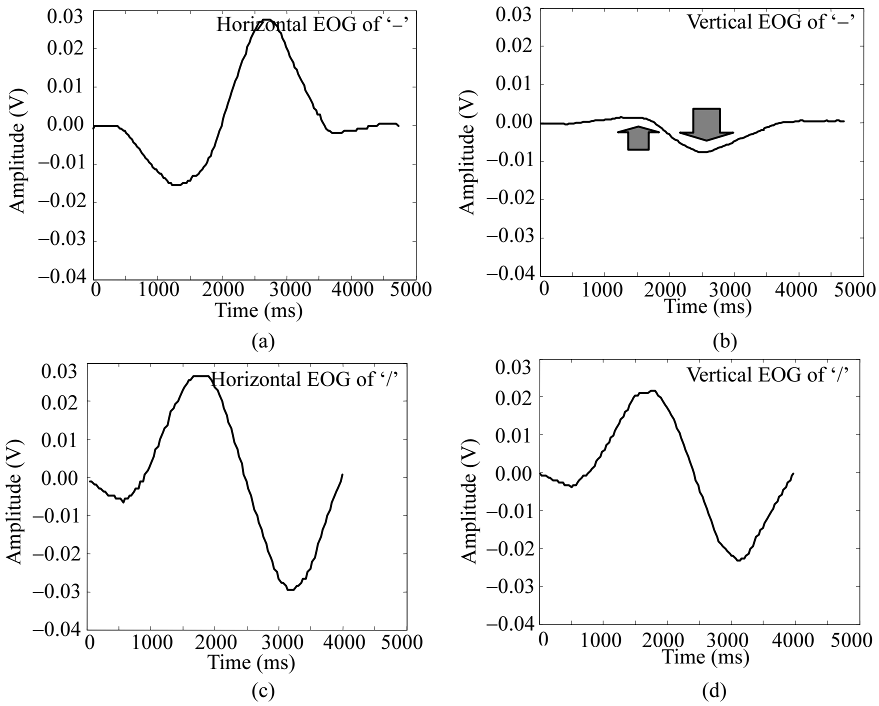


Figure 5. (a) The horizontal EOG signals of symbol ‘–’. (b) The corresponding vertical EOG signal of symbol ‘–’. The arrow heads indicate exposed crosstalk from the horizontal EOG. (c) The horizontal EOG signal of symbol ‘/’. The waveform contained unexposed crosstalk from the other direction. (d) The corresponding vertical EOG signal of symbol ‘/’. The waveform contained unexposed crosstalk from the other direction.

4) Classifying according to the turn count: The symbols were divided into nine clusters as shown in Table 1. This clustering was based on the *horizontal turn count (HTC)* and the *vertical turn count (VTC)* of individual symbols, which were defined as:

$$HTC = \begin{cases} +k_H, \textit{if the symbol trace turned right first} \\ -k_H, \textit{if the symbol trace turned left first} \end{cases} \quad (2)$$

and

$$VTC = \begin{cases} +k_V, \textit{if the symbol trace turned up first} \\ -k_V, \textit{if the symbol trace turned down first} \end{cases} \quad (3)$$

where k_H and k_V are the number of turns in the horizontal and the vertical direction, respectively, of the symbol trace. They reflected the changes of eye-movement directions in the horizontal and the vertical direction, respectively, when the symbol was eye-written. For example, the eyes turned left first, then right, and finally left when they wrote symbol ‘0’, so the *HTC* of symbol ‘0’ was −3. Similarly, ‘4’, ‘7’, ‘+’, and ‘$+_a$’ all got −3 in *HTC*, and so they belonged to the same cluster.

When processing an EOG signal, the system calculated the *HTC* or the *VTC* by first deducing a *slope sequence ss(n)* as follows:

$$ss(n) = \begin{cases} +1, & \textit{if } g(n) - g(n-1) \geq 0.00002 \\ -1, & \textit{if } g(n) - g(n-1) \leq -0.00002 \\ 0, & \textit{otherwise} \end{cases} \quad (4)$$

where *g(n)* is the horizontal or vertical EOG signal. The value 1 in *ss(n)* represents a rising slope in *g(n)*, whereas −1 in *ss(n)* indicates a declining slope in *g(n)*; 0 in *ss(n)* meant the slope at that instant was too small to be treated as a rising or a declining slope.

The slope sequence was smoothed with a moving-average operation in order to eliminate possible spikes toward the opposite direction. The *smoothed slope sequence sss(n)* is defined as:

$$sss(n)=\begin{cases} +1, & if \ \sum_{k=0}^{99} ss(k+n) \geq +50 \\ -1, & if \sum_{k=0}^{99} ss(k+n) \leq -50 \\ 0, & otherwise \end{cases} \qquad (5)$$

The value of k_H or k_V, and thus the magnitude of *HTC* or *VTC*, was obtained by counting the polarities of the *reduced sss(n)*, designated *rsss(n)*, which is defined as a sequence formed by keeping all nonzero elements whereas eliminating all zero elements in *sss(n)*.

Figure 6 shows an example of this step. The slope sequence *ss(n)* and the corresponding *sss(n)* and *rsss(n)* of a horizontal EOG signal of ‘0’ are shown. Simply speaking, *rsss(n)* = (−1, ···, 1, ···, −1, ···) and thus $k_H = 3$. So, *HTC* of this EOG signal was −3 in accordance with its definition in (2).

5) Final recognition: The purpose of this step was to identify the symbol from the cluster that it was classified into in last step. An artificial neural network based on linear vector quantization (LVQ) [19] was used to do so. The inputs to the neural network were *HTC*, *VTC*, and the *joint turn count (JTC)*, whose definition is described below:

$$JTC=\begin{cases} +k_J, if \ the \ first \ nonzero \ element \ of \ jsss(n) \ is +1 \\ -k_J, if \ the \ first \ nonzero \ element \ of \ jsss(n) \ is -1 \end{cases} \qquad (6)$$

where *jsss(n)*, called *joint sss(n)*, was a sequence obtained by elementwisely multiplying the horizontal *sss(n)* by the vertical *sss(n)* and k_J was the turn count of the *reduced jsss(n)*, designated *rjsss(n)*, which was a sequence formed by keeping all nonzero elements whereas eliminating all zero elements in *jsss(n)*.

The output of the neural network was the system’s answer to the symbol recognition. Table 1 tabulates the parameters of the artificial neural networks for individual clusters.

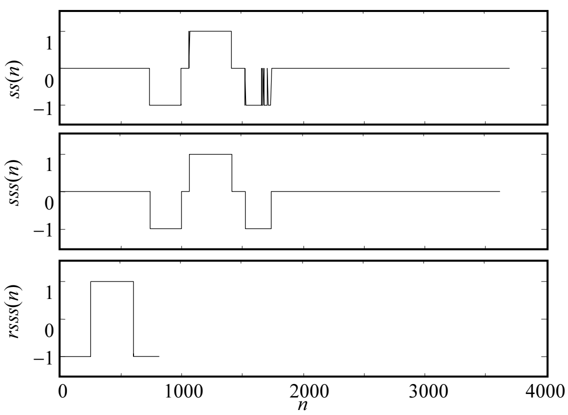


Figure 6. The slope sequence $ss(n)$, the smoothed slope sequence $sss(n)$, and the reduced smoothed slope sequence $rsss(n)$ for the horizontal EOG of an eye-written ‘0’.

Table 1. Clustering of symbols.

Cluster	Symbols	*HTC*	*VTC*	N_i	N_h	η
A	‘0’, ‘4’, ‘7’, ‘+’, ‘$+_a$’	−3	—	3	16	0.4
B	‘1’, ‘1_a’	0	—	—	—	—
C	‘2’, ‘5_a’	−5	—	3	4	0.5
D	‘3’, ‘5’	−6	—	3	4	0.5
E	‘6’, ‘$\times_a$’	−4	—	3	4	0.5
F	‘8’	+6	—	—	—	—
G	‘9’, ‘×’	+4	—	4	4	0.5
H	‘−’, ‘$-_a$’	—	0	—	—	—
I	‘/’, ‘0_a’	+3	—	3	4	0.5

HTC = horizontal turn count; *VTC* = vertical turn count; N_i = number of input-layer neurons; N_h = number of hidden-layer neurons; η = learning rate.

3. Results

Table 2 lists the results of our experiments on the eleven subjects. Every subject was asked to eye-write each symbol 5 times. This table only shows the misrecognized symbols. For example, among the 5 times of the eye-written ‘2’ by subject **e**, three were correctly recognized, one was misrecognized as ‘3’, and the other one was misrecognized as ‘5’. For another example, subject **a** eye-wrote ‘0’ 5 times without any misrecognition.

We evaluated the system’s recognition rate in terms of *dependability* (D_s) and *believability* (B_s). The dependability was defined as:

$$D_s = \text{Probability } \{Output\ symbol = s \mid Target\ symbol = s\} \qquad (7)$$

where $s \in S$, the symbol set defined in (1).

The system’s dependability with individual symbols eye-written by each subject can be induced from the raw results shown in Table 2. Table 3 tabulates values of the dependability thus obtained. The last column of this table shows the average dependability with each individual symbol. The last row of the same table shows the average dependability for each individual human subject. The overall average of the system’s dependability was 72.1%, shown as the last element in this table.

Table 4 lists the possible output symbols corresponding to each eye-written target symbol along with the probabilities of the output symbols. For example, when ‘7’ (the target symbol) was eye-written, with 65.6% probability it would be correctly recognized as ‘7’, whereas would be misrecognized as ‘0’ with a probability of 10.9%, ‘4’ with a probability of 3.6%, or ‘+’ with a probability of 20%. This table was also derived from the raw results in Table 2.

Table 5 lists the system’s believability for each output symbol, which was defined as:

$$B_s = \text{Probability } \{Target\ symbol = s \mid Output\ symbol = s\} \qquad (8)$$

where $s \in S$. The values in this table were also derived from the raw results in Table 2.

Table 2. Output symbols due to misrecognization.

Target symbols	Human subjects a	b	c	d	e	f	g	h	i	j	k
‘0’		‘+’, ‘+’	‘7’, ‘/’	‘/’		‘7’, ‘7’	‘7’	‘7’, ‘+’	‘7’, ‘7’, ‘/’	‘7’, ‘7’	‘/’
‘1’					‘/’		N				
‘2’			‘3’, ‘3’	N	‘3’, ‘5’	‘5’	‘5’,N	N,N	‘3’	‘3’, ’3’	
‘3’	‘5’	‘5’, ‘5’, ‘5’	‘5’, ‘5’, ‘5’	‘5’,N	‘5’, ‘5’, ‘5’	‘5’, ‘5’	‘5’, ‘5’, ‘5’	‘5’, ‘5’	‘5’	‘5’, ‘5’, ‘5’	‘5’
‘4’			‘7’	‘0’	‘0’, ‘0’	‘0’	‘0’,N	‘0’	‘0’	‘0’, ‘7’	
‘5’	‘3’,N	‘2’, ‘2’, ‘3’	‘3’, ‘3’	‘3’, ‘3’, ‘3’	‘3’	‘2’, ‘2’, ‘3’	‘2’, ‘3’, ‘3’,N	‘2’, ‘3’	‘2’, ‘2’, ‘3’, ‘3’	‘2’	‘3’, ‘3’
‘6’			‘4’	‘0’, ‘4’	‘4’	‘4’, ‘4’	‘0’, ‘4’	‘4’	‘0’, ‘4’	‘0’, ‘0’, ‘4’	‘7’
‘7’		‘+’, ‘+’, ‘+’	‘0’, ‘+’	‘+’, ‘+’	‘0’	‘4’, ‘+’	‘0’, ‘+’	‘0’, ‘+’, ‘+’	‘4’	‘0’, ‘0’	‘+’
‘8’		‘2’,N	‘2’, ‘2’	‘2’			‘2’,N	‘2’	‘2’	‘2’, ‘2’	
‘9’	‘×’, ‘×’		‘×’	‘×’,N	‘×’, ‘×’	‘2’, ‘×’	‘×’, ‘×’, ‘×’	‘×’, ‘×’	‘×’, ‘×’, ‘×’	‘×’, ‘×’,N	‘×’, ‘×’
‘+’	‘7’		‘7’	‘4’, ‘7’	‘7’, ‘7’	‘7’	‘0’, ‘7’, ‘7’	‘4’	‘0’, ‘0’, ‘0’	‘7’, ‘7’	‘7’, ‘7’
‘—’						N	N				
‘×’	‘9’, ‘9’	‘6’, ‘6’, ‘9’	‘9’	‘9’, ‘9’	‘6’, ‘6’	‘9’, ‘9’,N	‘9’, ‘9’, ‘9’	‘6’, ‘6’, ‘9’	‘2’	‘9’, ‘9’	‘6’
‘/’			N		‘2’, ‘6’	N	N,N	‘6’,N	N	‘6’, ‘6’,N	

Note: Every target symbol was eye-written by each subject 5 times. “N”: not recognizable.

Table 3. Dependability of the system (%).

Target symbols	Human subjects a	b	c	d	e	f	g	h	i	j	k	Average
‘0’	100	60	60	80	100	60	80	60	40	60	80	70.9
‘1’	100	100	100	100	80	100	80	100	100	100	100	96.4
‘2’	100	100	60	80	60	80	60	60	80	60	100	76.4
‘3’	80	40	40	60	40	60	40	60	80	40	80	56.4
‘4’	100	100	80	80	60	80	60	80	80	60	100	80.0
‘5’	60	40	60	40	80	40	20	60	20	80	60	50.9
‘6’	100	100	80	60	80	60	60	80	60	40	80	72.7
‘7’	100	40	60	60	80	60	60	40	80	60	80	65.6
‘8’	100	60	60	80	100	100	60	80	80	60	100	80.0
‘9’	60	100	80	60	60	60	40	60	40	40	60	60.0
‘+’	80	100	80	60	60	80	40	80	40	60	60	67.3
‘—’	100	100	100	100	100	80	80	100	100	100	100	96.4
‘×’	60	40	80	60	60	40	40	40	80	60	80	58.2
‘/’	100	100	80	100	60	80	60	60	80	40	100	78.2
Average	88.6	77.1	72.3	72.3	71.4	70.0	55.7	68.6	68.6	61.4	84.3	72.1

Table 4. Distribution of output symbols (%).

Target symbols	Output symbols ‘0’	‘1’	‘2’	‘3’	‘4’	‘5’	‘6’	‘7’	‘8’	‘9’	‘+’	‘—’	‘×’	‘/’	N
‘0’	70.9							16.4			5.5			7.2	
‘1’		96.4												1.8	1.8
‘2’			76.4	10.9		5.4									7.2
‘3’				56.4		41.8									1.8
‘4’	14.5				80.0			3.6							1.8
‘5’			16.4	29.1		50.9									3.6
‘6’	9.1				16.4		72.7								1.8
‘7’	10.9				3.6			65.6			20.0				
‘8’			16.4						80.0						3.6
‘9’			1.8							60.0			34.5		3.6
‘+’	7.3				3.6			21.8			67.3				
‘—’												96.4			3.6
‘×’			1.8				12.7			25.6			58.2		1.8
‘/’			1.8				7.3							78.2	12.7

“N”: not recognizable.

Table 5. Average believability.

Output symbol	Average believability (%)
‘0’	62.9
‘1’	100
‘2’	77.8
‘3’	50.0
‘4’	77.2
‘5’	51.9
‘6’	88.9
‘7’	57.1
‘8’	100
‘9’	62.3
‘+’	69.8
‘—’	100
‘×’	62.0
‘/’	97.7
Average	75.5

4. Discussion

4.1 Dependability and believability

The dependability and the believability were defined in this research as the indices of the system’s recognition rate. The dependability was defined from the viewpoint of the direct user, such as an ALS patient. An eye-writing system with a higher dependability is more capable of outputting a correct symbol that matches the target symbol eye-written by the user, and so the direct user feels more comfortable in depending on the system to write. On the other hand, the believability was defined from the viewpoint of the indirect user, i.e., the person communicating with the direct user. An output symbol from an eye-writing system with a higher believability matches the eye-written target symbol with a higher probability, and thus the output of the system is more believable to the person. The value of the dependability of the system with each target symbol and the value of the believability of the system with each output symbol have been tabulated in Tables 3 and 5, respectively. Their correlation depicted in Figure 7 gives a clear picture of how good the system was for each symbol. Symbols ‘1’ and ‘–’ among all attained the highest performance, almost 100% both in dependability and in believability, possibly because of their unique trace patterns. The lowest recognition was with ‘3’ and ‘5’, with nearly 50% in dependability and believability. Looking back to Table 4, we see that 41.8% of the eye-written ‘3’s were misrecognized as ‘5’s and 29.1% of the eye-written ‘5’s were misrecognized as ‘3’s. The similarity in their trace patterns and thus in their EOG waveforms explains the low recognition rates of these two symbols. It is noteworthy that this can be avoided by changing the predefined trace of either symbol ‘3’ or symbol ‘5’. There was disparity between the dependability and the believability for symbol ‘8’. When it was eye-written, with 16.4% probability it was misrecognized as ‘2’ and unrecognizable with 3.6% probability, as shown in Table 4. So, the dependability for it was 80%. Nevertheless, it got 100% believability because no other eye-written symbol was misrecognized as it. Conversely, the other type of disparity will happen if a symbol is not misrecognized easily when it is eye-written but other eye-written symbols are easily misrecognized as it. The dependability will be high but the believability will be low with such a symbol.

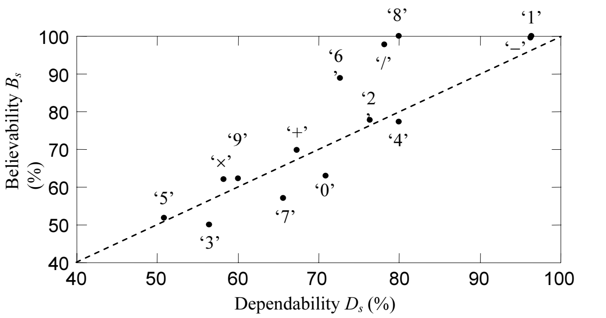


Figure 7. The correlation of the dependability and the believability of the eye-writing system for each individual symbol. The dashed line represents $D_s = B_s$.

4.2 Feasibility

The recognition rate of the system (Fig. 7) seems low, with the dependability (D_s) and the believability (B_s) of most symbols being lower than 80%. However, it would be too soon to jump into the conclusion that a useful eye-writing system is infeasible. In fact, the human subjects in this research had no previous experience in eye-writing, and they only practiced it for fewer than 10 symbol traces or even did not practice before doing the experiment. In reality, the recognition rate would rise if the user practiced for a period of time to let their eyes get used to eye-writing and to adapt their eye-writing habits to the recognition algorithm. For example, the authors normally attained higher than 95% recognition rates due to frequent eye-writing required in ordinary experiments while developing the system. Besides user practicing, another way to improve the recognition rate would be to let the system accommodate to individual users through calibration and changing of parameters, or even through the use of different algorithms.

4.3 Advantages

Without the need for a symbol matrix display, the eye-writing method is advantageous compared to other communication methods through the eyes [13-16] in at least two aspects. First, it is more portable. A practical eye-writing system can simply consist of the electrodes, the amplification circuit, the analog-to-digital converting circuit, a micro-processor, plus a speaker or a small liquid crystal display to show the output symbols. Second, the cost of an eye-writing system will be lower, and hence an economical system affordable by most ALS patients is more probable based on the eye-writing method than based on other methods.

The eye-writing method makes the eye-movement-based communication more versatile and useful. For example, in controlling a wheelchair, the eye-writing method can be used to output the instructions while other methods can be used to control the moving direction of the wheelchair.

4.4 Baseline drift

There has not been an easy and effective method to prevent baseline drift from happening. We compensated for baseline drift by subtracting from the EOG signal an estimated baseline drift that was obtained by connecting the average of the first several samples and that of the last several samples of a symbol’s EOG signal. This diminished the influence of the baseline drift to a large extent. However, we were still plagued by baseline drift, especially in the vertical EOG signal, sometimes when it became large enough to drive the amplification circuit into saturation. Fortunately, it only caused temporary malfunction of the system for several minutes, which was quite tolerable in most cases. We also found in our experiments that saturation occurred more easily when the human subject’s body felt hot. When this happened, cooling down by fans did help a lot reduce the baseline drift and reestablish the circuit function.

4.5 Blinking

Eye blinking added to the EOG signal spurious pulses, which might result in misrecognition. Figure 8 exemplifies the artifacts due to eye blinking. In this study, no remedy was used to deal with the eye blinking that contaminated the EOG signals. Indeed, we required that the subjects refrained from blinking their eyes while doing eye-writing. In the future development of the system to accommodate continuous symbols writing, we plan to allow the users to blink their eyes between the eye-writings of two consecutive symbols while still disallowing the eye blinking during the eye-writing of each symbol. The time of the eye blinking will be detected by extracting its corresponding electromyogram (EMG) from the EOG signal with a filter [14]. Knowing the time of blinking will enable further processing to prevent the artifacts from causing misrecognition.

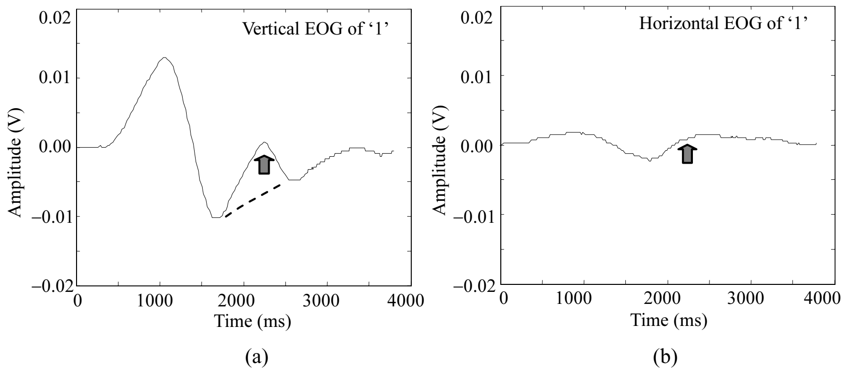


Figure 8. (a) The vertical and (b) the horizontal EOG signals acquired when a subject was eye-writing symbol '1'. The subject blinked the eyes at about 2200 ms. The arrow heads indicate spurious pulses caused by the eye blinking. The dashed line is the expected waveform without blinking. The blinking effect was not apparent in the horizontal signal; it was blurred by the crosstalk from the vertical channel.

5. Conclusion

We conclude that an eye-writing system is feasible, considering that the recognition rate associated with a symbol can be raised by properly designing the symbol trace. The symbol set can be optimized by only including the symbols of high recognition rates, that training and practicing can improve the user's eye-writing ability. The system parameters can be calibrated to suit different users, and that the recognition algorithm can be adjusted to accommodate to the individual user's eye movement ability.

Envisioning the portability, economy, and versatility concomitant of the eye-writing method, our future research will aim at an eye-writing system usable for ALS patients. The symbol set in our future system will adopt all the Chinese punctuation symbols and all the English letters. We used disposable adhesive electrodes to acquire the EOG signals in this research. In the future system, however, electrodes embedded in an eyeglasses frame would be preferred in view of the patients' convenience and economy. Noncontact methods based on infrared image acquisition are also worth consideration.

References

[1] J. W. Clark, Jr., The origin of biopotentials, in J. G. Webster (Ed.), *Medical Instrumentation: Application and Design (3rd Ed.)*, New York: John Wiley & Sons: 121-182, 1998.

[2] C. J. Lin, C. H. Yang, C. M. Yang and K. P. Chang, "Abnormal electroretinogram and abnormal electrooculogram after lightning-induced ocular injury," *Am. J. Ophthalmol.*, 133: 578-579, 2002.

[3] C. F. Arndt, P. Derambure, S. Defoort-Dhellemmes and J. C. Hache, "Outer retinal dysfunction in patients treated with vigabatrin," *Neurology*, 52: 1201-1205, 1999.

[4] M. Bareš, M. Brázdil, P. Kanovský, P. Jurák, P. Daniel, M. Kukleta and I. Rektor, "The effect of apomorphine administration on smooth pursuit ocular movements in early Parkinsonian patients," *Parkinsonism Relat. Disord.*, 9: 139-144, 2003.

[5] F. W. Bylsma, D. X. Rasmusson, G. W. Rebok, P. M. Keyl, L. Tune and J. Brandt, "Changes in visual fixation and saccadic eye movements in Alzheimer's disease," *Int. J. Psychophysiol.*, 19: 33-40, 1995.

[6] N. Ozaki, N. E. Rosenthal, F. Myers, P. J. Schwartz and D. A. Oren, "Effects of season on electro-oculographic ratio in winter seasonal affective disorder," *Psychiatry Res.*, 59: 151-155, 1995.

[7] R. Carniel, E. D. Pin, R. Budai and P. Pascolo, "Identifying timescales and possible precursors of the awake to asleep transition in EOG time series," *Chaos Solitons Fractals*, 23: 1259-1266, 2005.

[8] R. Barea, L. Boquete, M. Mazo and E. López, "System for assisted mobility using eye Movements based on electrooculography," *IEEE Trans. Neural Syst. Rehabil. Eng.*, 10: 209-218, 2002.

[9] R. Barea, L. Boquete, M. Mazo, E. Lopez and L. M. Bergasa, "EOG guidance of a wheelchair using neural networks," *Proc. 15th Int. Conf. on Pattern Recognition*, 4: 668-671, 2000.

[10] Y. Kim, N. Doh, Y. Youm and W. K. Chung, "Development of human-mobile communication system using electrooculogram signals," *Proc. 2001 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 4: 2160-2165, 2001.

[11] J. J. Gu, M. Meng, A. Cook and M. G. Faulkner, "A study of natural eye movement detection and ocular implant movement control using processed EOG signals," *Proc. 2001 IEEE Int. Conf. on Robotics and Automation*, 2: 1555-1560, 2001.

[12] C. Armon, *ALS 1996 and Beyond: New Hopes and Challenges (A manual for patients, families, and friends) (Third (Year 2000) Ed.)*, CA: Loma Linda University, 1999. Available: http://www.llu.edu/llumc/neurosciences/als/index.html.

[13] K. Yano, K. Ishihara, M. Makikawa and H. Kusuoka, "Detection of eye blinking from video camera with dynamic ROI fixation," *Proc. IEEE '99 Int. Conf. on Systems, Man, and Cybernetics*, 335-339, 1999.

[14] Y. Tomita, Y. Igarashi, S. Honda and N. Matsuo, "Electro-oculography mouse for amyotrophic lateral sclerosis patients," *Proc. of the 18th Annual Int. Conf. on the IEEE Engineering in Medicine and Biology Society*, 5: 1780-1781, 1996.

[15] J. J. Tecce, J. Gips, C. P. Olivieri, L. J. Pok and M. R. Consiglio, "Eye movement control of computer functions," *Int. J. Psychophysiol.*, 29: 319-325, 1998.

[16] T. Maehara, A. Uchibori, Y. Mizukami, Y. Wakasa and K. Tanaka, "A communication system for ALS patients using eye-direction," *IEEE EMBS Asian-Pacific Conf. on Biomedical Engineering*, 274-275, 2003.

[17] E. E. Sutter, "The brain response interface: communication through visually-guided electrical brain responses," *J. Microcomput. Appl.*, 15: 31-45, 1992.

[18] L. A. Farwell and E. Donchin, "Talking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials," *Electroenceph. Clin. Neurophysiol.*, 70: 510-523, 1988.

[19] T. Kohonen, "The self-organizing map", *Proc. of the IEEE*, 78: 1464-1480, 1990.