Numerical study on adjusting parameters to improve gaze estimation using planar approximations from electro-oculogram signal voltage ratios

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Abstract

Gaze or eye movements are used as a communication interface in daily life. Herein, we developed a simple method for gaze estimations based on planar approximations of voltage ratios calculated from multiple electro-oculogram signals not affected by drift phenomena, which decrease accuracy. Subsequently, we conducted simulations using an eyeball battery model and investigated the effects of adjusting electrode arrangements, determination coefficients for planar approximations of voltage ratios, and threshold values for angles between simultaneous linear equations, to improve the estimation accuracy and decreased the number of required electrodes. Numerical experiments were used to identify arrangements of six electrodes with errors that were approximately 5° less than those of nine-electrode L-shaped arrangements, indicating improved estimation accuracy with fewer electrodes.

Keywords Gaze estimation · Electro-oculography · Planar approximation · Voltage ratio · Numerical experiment

1 Introduction

The aim of this study was to develop a method for gaze estimations in horizontal and vertical planes using electro-oculogram (EOG) signals. Previously, we proposed a method for gaze estimations based on approximations of voltage ratios from multiple EOG signals [1]. However, large numbers of electrodes were required for successful estimation. Thus, in the present study, we performed numerical experiments to inform adjustments of parameters for gaze estimations that improved estimation accuracy and decreased the number of electrodes required.

Gaze and eye movements are an important communication tool for patients with severe cervical spine injuries or muscular dystrophies, such as amyotrophic lateral sclerosis [2–8]. Eye movements can be measured using methods including the corneal reflex, scleral reflection, video-oculography, and electro-oculography. However, strain levels in

subjects vary among these measurement methods. Specifically, the former three methods require examiners to fix the positions of both the measurement device and the subject, and the eye gaze is interrupted by the device during measurement. Meanwhile, electro-oculography does not require examiners to set up the device or fix the subject's position; it only requires them to place electrodes around the eyes of subjects. Although the former three methods measure eye gaze more precisely than electro-oculography, the latter method causes less strain to the subject.

Electro-oculography is used to estimate gaze direction and employs relationships with measured voltages between two electrodes attached to the skin around the eyes [9]. However, owing to drift of baseline EOG signals, conventional estimates of absolute gaze directions often lack accuracy. Thus, assessments of gaze gestures using four- or eight-direction pointing systems [10–12] and activity recognition [13] have been developed as communication devices, although their absolute estimation accuracy is low. By contrast, techniques based on nonlinearity of EOG signals and gaze directions allow the estimation of absolute horizontal gaze directions to approximately 4°, using seven electrodes [14]. Another study enhanced the performance of the interface by removing the interdependency of the EOG components [15].

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Previously, we proposed gaze estimation methods using voltage ratios of EOG signals amplified in a direct-coupled manner to minimize the influence of drift. These methods are based on line [16] and planar approximations [1] of voltage ratios and can be used to estimate absolute gaze in the horizontal direction and in the horizontal and vertical planes, respectively. Numerical experiments under noise conditions revealed that the present planar approximation method estimates gaze direction with an error of approximately 9° , using at least nine electrodes arranged in an L-shape (Fig. 1a). However, in preliminary experiments it was difficult to accurately attach nine electrodes to one eye. Therefore, methods that use fewer electrodes without losing estimation accuracy are required.

In this study, we investigated adjustments of the parameters for gaze estimations based on planar approximations of EOG voltage ratios. In subsequent numerical experiments

performed using an eyeball battery model [17], we identified a set of parameters that allowed estimates with five-degree improvements in accuracy, using only six electrodes.

2 Methods

Gaze estimations were performed using planar approximations of voltage ratios from multiple EOG signals. The detailed estimation method is as follows [1]. We defined θ and ξ as the horizontal and vertical angles of the gaze, respectively. The ratios Vr of EOG signals between two arbitrary electrodes selected from more than three electrodes were approximated in a planar manner using the horizontal and vertical gaze angles as variables:

$$Vr = C_\theta \theta + C_\xi \xi + C_B. \quad (1)$$

The least-squares method was used to calculate the coefficients C_θ , C_ξ , and C_B . We also calculated the determination coefficient for the planar approximation. Only Vr s above the determination coefficient thresholds D_{th} were used for gaze estimation, and θ and ξ were recorded for each Vr value.

When more than two Eqs. (1) with different Vr were obtained, two equations were randomly selected. If the angle between the two equations exceeded the threshold value A_{th} , the simultaneous linear equations were solved for θ and ξ . When θ and ξ were within the range of the approximated eye-gaze directions recorded above, θ and ξ were accepted as valid; if not, they were discarded. When several pairs of θ and ξ were obtained, the mean values of θ and ξ were calculated as the estimated gaze, and we defined this as a successfully estimated gaze. If there were fewer than two linear equations for θ and ξ or if all pairs of θ and ξ were discarded, we could not determine an estimation, which was as defined as a failed estimation.

To determine the accuracy of estimates using various parameters, including electrode arrangements, the planar approximation threshold D_{th} , and the angle threshold A_{th} were used to identify parameter sets that provide estimates using fewer than nine electrodes.

All electrode arrangements were placed around the right eye, at 20 attachment candidates (Fig. 1b, The origin of coordinates (0, 0, 0) was the center of the right eyeball). Subsequently, determination coefficient thresholds D_{th} for voltage-ratio planar approximations were set at 0.8, 0.85, 0.9, and 0.95, and A_{th} angle thresholds were set from 0 to 30° at intervals of 5° .

Numerical experiments were performed using an eyeball battery model with only the right eye, which mimics the potential difference between the cornea and the retina [17]. Voltage V of electrodes at distances r and r' from positive and negative poles, respectively, is expressed as follows in Eq. (2); Fig. 1c

Fig. 1 **a** Nine-electrode L-shaped arrangement. **b** Candidate electrode attachments around the right eye. **c** An eyeball battery model. **d** Range of eye-gaze directions. Origin of the coordinates is the center of the right eye. θ and ξ define degrees of yaw and pitch directions of gaze, respectively

$$V = \frac{I}{4\pi\sigma} \left(\frac{1}{r} - \frac{1}{r'} \right) \quad (2)$$

where I is the electric current from the retina to the cornea within the eyeball and σ is the electric conductivity of the uniform media within and surrounding the eyeball. Then, the voltage between electrodes 1 and 2 is expressed as follows,

$$\Delta V = V_1 - V_2 = \frac{I}{4\pi\sigma} \left\{ \left(\frac{1}{r_1} - \frac{1}{r'_1} \right) - \left(\frac{1}{r_2} - \frac{1}{r'_2} \right) \right\}. \quad (3)$$

Previous studies showed that the voltage between two points in the battery model of the eyeball with uniform conductivity closely approximates the measured data [17]. Thus, the battery model is useful for simulating EOG signal generation.

The change of the electric current from the retina to the cornea, which causes signal drift, is correlated with temporal changes of the current density I in Eq. (3). Thus, the current density is removed from the ratios of ΔV , which can be used as an index of the gaze estimation with minimized signal drift.

To simulate the gaze estimation, we first calculated voltages at each electrode and the ratios from Eqs. (2) and (3) at known θ and ξ angles to calibrate the planar voltage ratios using Eq. (1). Second, we estimated the gazes using the calculated voltages from Eqs. (2) and (3) at various θ and ξ angles to investigate the estimation characteristics, i.e. the measured EOG data. Finally, we investigated the basic estimation characteristics; namely, we calculated the mean absolute errors of the estimated gaze direction, defined as the absolute value of the difference between the obtained and correct values averaged over the gaze range, and the success rate of estimation, i.e., the number of successful θ and ξ estimates relative to the total number of targets.

The range of gaze direction θ was defined at -40° to 40° and ξ was defined at -30° to 30° (Fig. 1d). To calibrate planar voltage ratios, we calculated voltage ratios at various θ and ξ angles in (5, 5)-degree intervals (221 or 17×13 points), (8, 7.5)-degree intervals (99 or 11×9 points), (10, 10)-degree intervals (63 or 9×7 points), and (16, 15)-degree intervals (30 or 6×5 points), respectively. Subsequently, we investigated basic estimation characteristics within a range of gaze with one-degree changes in gaze direction. The total number of targets was 4941 (81×61 points).

We also added random noise to electric potentials at each electrode (fluctuations of contact impedance), bias noise to voltages between two electrodes (bias of the amplitude coefficient in whole amplification circuits), and bias noise to the magnitude of displacements at random directions from the electrode location.

In numerical experiments, electric noise in each electrode was defined as $N(0, 10^2 \mu V^2)$ and the same bias noise value

of $10 \mu V$ was added to all the voltages. The magnitude of electrode location displacement was set at 1 mm. Estimates were made according to mean estimation errors and success rates from 50 measurement trials.

In the present battery model, the eyeball radius was 12 mm and $I/4\pi\sigma$ was $25 \mu Vm$. We did not consider electrode sizes. Programs for all numerical experiments were written in the C language (gcc 4.2.1, macOS10.13).

3 Results

The estimation error in the L-shaped arrangement with nine electrodes was approximately 8.8° with D_{th} and A_{th} values of 0.9 and 0° , respectively [1]. We investigated the estimation errors and the success rates of estimation by changing the number of electrodes. The number of the electrode arrangements was 1140; 4845; 15,504; and 38,760 with three, four, five, and six electrodes, respectively. Figure 2 shows the average errors and rates in all arrangements with three, four, five and six electrodes with D_{th} and A_{th} values of 0.9 and 0° , respectively and 221 reference points for calibration. We note that the vertical range in Fig. 2 is from 0° to 10° , although we found estimation errors above 10° . We selected this range because we focused on errors less than 8.8° with the nine-electrode L-arrangement.

In the case of three electrodes (Fig. 2a), the number of arrangements in which the gaze could be estimated was 266. The minimum estimation error was 6.4° , but the success rate was 2.9%. On the other hand, the maximum success rate was 44%, and the estimation error was 23° . Although the estimation error in four-electrode arrangements is smaller

Fig. 2 Results with the mean estimation error and the success rate in the numerical experiments with determination and angle threshold values of 0.9 and 0° , with 221 reference points for calibration. The numbers of electrodes are 3, 4, 5, and 6 for **a**, **b**, **c**, and **d**, respectively

than that in L-shaped arrangements with nine electrodes, the success rate was less than 3% in either case. In the case of four electrodes (Fig. 2b), the number of arrangements in which the gaze could be estimated was 4625. The minimum estimation error was 3.0° , but the success rate was 2.6%. On the other hand, the maximum success rate was 85%, and the estimation error was 12° . Although the estimation error in 1218 arrangements is smaller than that in L-shaped arrangements with nine electrodes, the success rate was less than 62% in either case.

In the case of five electrodes (Fig. 2c), the number of arrangements in which the gaze could be estimated was 15,497. Of these, 18 arrangements had the success rates of 95% or higher. The minimum estimation error was 4.2° , but the success rate was 67%. On the other hand, the maximum success rate was 98%, and the estimation error was 14° . The estimation error in 4403 arrangements is smaller than that in L-shaped arrangements with nine electrodes. Among the arrangements, the number of arrangements with the success rate of 95% or more was one; the estimation error and the success rate were 7.6° and 96%, respectively.

In the case of six electrodes (Fig. 2d), the number of arrangements in which the gaze could be estimated was 48,759. Of these, 9252 arrangements had the success rates of 95% or higher; 1058 arrangements had the success rates of 99% or more. The minimum estimation error was 4.6° , but the success rate was 99%. The estimation error in 759 arrangements is smaller than that in L-shaped arrangements with nine electrodes with the success rate of 99% or higher.

We focused on the 759 arrangements with six electrodes and investigated the influence of the estimated parameters D_{th} and A_{th} and the number of reference points during calibration.

Figure 3a, b show the average estimation error and the average success rate over the 759 arrangements for varying D_{th} determination thresholds with A_{th} of 0° and 221 reference points for calibration. We found that the estimation error decreased slightly for D_{th} varying from 0.8 to 0.9 and increased for a D_{th} value of 0.95 and that the variations in

Fig. 3 Results of gaze-estimation experiments with changing determination threshold values at angle threshold of 0° , with 221 reference points for calibration. **a** and **b** Denote the averaged error and the success rate over 759 arrangements with six electrodes, respectively

the error were almost independent on the value of D_{th} . On the other hand, although with D_{th} varying from 0.8 to 0.9, the success rates were maintained at approximately 100%, at a D_{th} of 0.95, the rates decreased approximately 10% and the variation in the rate was large.

Figure 4a, b show the average estimation error and the average success rate over the above 759 arrangements with various A_{th} angle thresholds at a D_{th} of 0.9 and 221 reference points for calibration. As A_{th} increased, the estimation error decreased; the error decreased by approximately 1.5° for A_{th} varying from 0 to 30° . The variation of the error hardly changed with the value of A_{th} . As A_{th} increased, the success rates also decreased; the rate decreased by approximately 4% for A_{th} varying from 0 to 30° , and the variation gradually increased.

Figure 5a, b show the average estimation error and the average success rate over the above 759 arrangements with various reference points for calibration with $D_{th}=0.9$ and $A_{th}=0^\circ$. As the number of the reference points decreased, the estimation errors increased; the amount of the increase was approximately 1.4° from 221 points to 30 points. The variation of the error increased at 30 points. On the

Fig. 4 Results of gaze-estimation experiments with changing angle threshold values at determination threshold of 0.9 and 221 reference points for calibration. **a** and **b** Denote the averaged error and the success rate over 759 arrangements with six electrodes, respectively

Fig. 5 Results of gaze-estimation experiments with changing numbers of reference points for calibration at 0.9 and 0° degree of determination and angle thresholds. **a** and **b** Denote the averaged error and the success rate over 759 arrangements with six electrodes, respectively

Fig. 6 Three most accurate arrangements for the right eye with six electrodes over various arrangements and determination and angle threshold values at 221 reference points for calibration

Fig. 7 Estimation error with gaze ranges **a** for electrode arrangement in Fig. 6a, determination threshold of 0.9, and angle threshold 30°; **b** for Fig. 6b, 0.9, and 25°; and **c** for Fig. 6c, 0.9, and 30°. The number of reference points for calibration is 221

other hand, the success rates hardly changed except for the increase of the variation at 30 points.

Next, we found the combination with the least error among the combinations of electrode arrangements, D_{th} values, and A_{th} values. The estimation error and the success rate of the top three at the combination with the least estimation error were 3.71° and 97.1% with respect to Fig. 6a, 0.9, and 30° of the electrode arrangements, determine threshold D_{th} , and angle threshold A_{th} , respectively, 3.93° and 97.9% with respect to Fig. 6b, 0.9, and 25°, and 3.99° and 97.4% with respect to Fig. 6c, 0.9, and 30°. With respect to D_{th} and A_{th} , we obtained the values of 0.9 and 25 or 30° as shown in Figs. 3 and 4. With respect to the electrode arrangements, we found that in Fig. 6a, there were five electrodes in the lower part of the eye, in particular three electrodes on the ear side and one electrode in the upper part, and that the arrangements in Fig. 6b, c were similar and the electrodes were arranged relatively evenly around the eye.

Figure 7a–c illustrate estimation errors within a range of gaze directions for electrode arrangements, D_{th} , and A_{th} with respect to (Fig. 6a, 0.9, 30), (Fig. 6b, 0.9, 25), and (Fig. 6c, 0.9, 30), respectively. The accuracy of estimation was high, with errors less than 2° in almost all ranges of gaze direction but was very low in the boundary regions of gaze directions with errors greater than 5° and with 3° to 5° for the ranges around θ of 15 and θ of 20° in Fig. 7a, θ of −20 and θ of 10°

in Fig. 7b, and θ of −20 and θ of 15° and θ above 30 and θ of 0° in Fig. 7c.

For practical use, it is important to clarify variables that influence individual differences in estimation performance. Parameters of the eyeball battery model, such as eyeball radii, current strength, positions of positive and negative poles, and distances between poles and the center of the eyeball can be adjusted. Thus, we conducted numerical experiments with 10% variations in all these parameters and found similar results to those in Figs. 2, 3, 4, 5, 6 and 7. These investigations revealed that small individual differences in the eyeball's size and shape as well as surroundings do not drastically influence gaze estimations in model simulations.

4 Discussion

In the present study, we defined parameters for gaze estimations using voltage ratios from multiple EOG signals that produce higher estimation accuracy with the estimated error of 3.7° with six electrodes than with nine electrodes in an L-shaped arrangement as previously reported [1]. Another method using the nonlinear feature of EOG signals [14] estimated the horizontal gaze direction of approximately 4° with seven electrodes. The present method allows realizing a similar estimation accuracy with fewer electrodes and in both horizontal and vertical gaze directions.

In comparison with previous errors [1] within a range of gaze directions (Fig. 7), regions with errors less than 2° were expanded, and the estimation accuracy in the central region was drastically improved. These data indicate that electrodes at the lower or upper ear-side locations (Fig. 6) improve estimation accuracy. However, the L-shaped arrangement includes electrodes at these locations, suggesting that the accuracy of the L-shaped arrangement is decreased by symmetrical arrangements of electrodes at nose-side locations. From the battery model equation (Eq. 2), when the distance between the electrode and the eyeball is equal, the EOG signals are equal. Therefore, when obtaining ratios of EOG signals, the ratios diverge and there is concern that they do not contribute to the gaze estimation.

For realizing a practical method of attaching electrodes, other studies [10, 11, 14] reported techniques using five to seven electrodes that contribute to estimation systems using goggles [10] or glasses [11]. In addition, the distances between electrodes in the arrangements shown in Fig. 6 were not smaller than those in L-shaped arrangements. Hence, these arrangements may be used in applications involving appropriate devices for accurate attachment of electrodes. Especially, arrangement in Fig. 6a requires attachment of four electrodes around a cheekbone under the eye. The skin around the cheekbone has less movement during blinking, which could lead to less noise

during measurement of EOG signals. However, it may be difficult to attach electrodes between the eye and nose due to the shift in position during blinking, which causes an estimation error. Therefore, it may be necessary to further consider the electrode arrangements and reduced the number of electrodes for practical use.

Relatively high regions for both thresholds in Figs. 3 and 4 improved the estimation accuracy and maintained high estimation success rates. Specifically, in the presence of high determination coefficient thresholds, planar approximation equations with large displacements from measured voltage ratios were excluded and accuracy was improved. Moreover, when the angle between the two linear equations was less than the angle threshold, solutions that differed markedly from the true direction were discarded and estimation accuracy was improved. However, large threshold values decreased the estimation success rates in some cases [1] and increased the variation in the success rate, especially at $D_{th} = 0.95$. As the threshold values increased, the number of planar approximated ratios decreased, as did the set of simultaneous equations used for estimation. When these numbers were low, estimation sometimes succeeded or failed due to noise. Thus, the variation was large. With respect to the reference points for calibration, a small number of the points, and thus, a long distance between points, leads to less stress for subjects. In Fig. 5, regardless of the number of reference points, the results with show only slight variation in the error, which is good in a practical sense. Therefore, we must further investigate whether the gaze can be estimated with the present method with fewer reference points.

5 Conclusion

In the present study, numerical experiments were used to adjust parameters for gaze estimations and improve estimation accuracy with fewer electrodes. Accordingly, numerical experiments performed using an eyeball battery model revealed a set of parameters for six electrodes that led to five-degree improvements in estimate errors, compared with those from nine-electrode L-shaped arrangements.

These observations warrant further study, to validate the present gaze estimation methods in human subjects. These experiments will be conducted with consideration of the effects of eye blinking, face muscle activity, crosstalk from other eye movements, and displacement of attached electrodes.

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Compliance with ethical standards

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