Direction and viewing area-sensitive influence of EOG artifacts revealed in the EEG topographic pattern analysis

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Abstract The influence of eye movement-related artifacts on electroencephalography (EEG) signals of human subjects, who were requested to perform a direction or viewing area dependent saccade task, was investigated by using a simultaneous recording with ocular potentials as electro-oculography (EOG). In the past, EOG artifact removals have been studied in tasks with a single fixation point in the screen center, with less attention to the sensitivity of cornea-retinal dipole orientations to the EEG head map. In the present study, we hypothesized the existence of a systematic EOG influence that differs according to coupling conditions of eye-movement directions with viewing areas including different fixation points. The effect was validated in the linear regression analysis by using 12 task conditions combining horizontal/vertical eye-movement direction and three segregated zones of gaze in the screen. In the first place, event-related potential topographic patterns were analyzed to compare the 12 conditions and propagation coefficients of the linear regression analysis were successively calculated in each condition. As a result, the EOG influences were significantly different in a large number of EEG channels, especially in the case of horizontal eye-movements. In the cross validation, the linear regression analysis using the appropriate dataset of the

target direction/viewing area combination demonstrated an improved performance compared with the traditional methods using a single fixation at the center. This result may open a potential way to improve artifact correction methods by considering the systematic EOG influence that can be predicted according to the view angle such as using eye-tracker systems.

Keywords Electroencephalogram (EEG) · Electro-oculogram (EOG) · Artifact correction · Linear regression analysis · Event-related potential (ERP)

Introduction

In the analysis of the brain activity by using EEG measurements, contamination of artifacts is a serious issue. Ocular and myographic potentials are known as the major artifacts in EEG measurements and ocular potentials are induced by eyeball and eyelid movements. The removal of ocular artifacts has been studied intensively. As a practical method in the past studies, subjects are requested to gaze at a fixed point in order to reduce the ocular artifacts. On the other hand, recent neuro-engineering studies, known as brain-computer-interface (BCI), requests EEG recordings under movable situations accompanied by eye movements (Wang et al. 2014; Borghini et al. 2014). The complete ocular artifact removal still remains unsolved. There are large expectations in free viewing EEG studies (Plöchl et al. 2012; Henderson et al. 2013; Kamienkowski et al. 2012) and analyses of cognitive functions such as memory retrieval (Talebi et al. 2012), language processing (Malaia and Newman 2015) and conscious state (Taylor 2007).

According to the morphology of eyeballs and the electrophysiology of extraocular muscles, the cornea-retinal

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potential is estimated as high a tens millivolts (Marmor and Zrenner 1993; Ding et al. 2005) and it was measured as hundreds micro-volts via electrodes attached around eyes as EOG recording channels (Dorf 2003; Shinomiya et al. 2008; Lins et al. 1993). In principle, the ocular potential stays at the certain level depending on the degree of eyeball rotations, which exhibited a linear relationship between the rotation degree and the ocular potential (Shinomiya et al. 2008). According to those electrophysiological evidences, effects of the ocular artifact were explained in the dipole model and the potential was spatially propagated over the scalp as a non-negligible influence to extracranial EEG recordings (Berg and Scherg 1991). In the simplest way, the EOG influence can be analyzed in the linear model of true EEGs and EOG multiplied by coefficient values, which directly represents how much the ocular potential is contaminated into individual EEG channels (Croft and Barry 2000; Gratton et al. 1983). The mechanism of ocular artifacts was considered as changes of ocular dipoles' orientation and moreover an interaction between eyeballs and eyelids which were observed as sliding electrode effects (Picton et al. 2000). In saccade tasks, EOG influences have been analyzed as event-related potentials and discussed by using the EEG topographic map (Picton et al. 2000; Keren et al. 2010; Carl et al. 2012), while the experiments were mostly based on task conditions with a single fixation point. It indicates that the ocular dipoles' orientation or view angle-dependent EOG influence is still unclear.

In order to improve EEG de-noising performance, in general, blind source separation, such as Independent Component Analysis (ICA), have been widely used (Urign and Garcia-Zapirain 2015), which requires a large number of EEG channels for accurate and confident analyses since the number of channels should be more than the number of independent components, for example, 121 EEG channels were practically used in the work reported by Winkler et al. (2011).

In the early stage investigation focusing on eye-movement related artifacts, Schlgl et al. (2007) examined the EOG influence in the tasks requiring subjects to perform clockwise and counter-clockwise eye movements, following the motion along a large circle centered on the screen with eyes, and their model involved three spatial EOG components of horizontal, vertical and radial axes in the three dimensional space. Plchl et al. (2012) investigated as more as eight types of eye movements that consist of small and large saccades in horizontal and vertical directions. In their task, trajectories of large saccades passed through the screen center and small saccades started or ended at the center. Interestingly, they demonstrated a topographic difference of ERPs in the comparison between upward and downward eye movements. However, it was

found there was no significant difference in comparison between small and large saccades. It suggested the directional selectivity of ocular artifacts to contain a further important clue to the presence of the sensitivity in zones of gaze if it would be beyond traditional center-fixed saccade tasks.

Hypothesis

In order to clarify the sensitivity of eye-movement related dipole orientations in EEGs, we proposed a novel systematic task to compare vertical and horizontal eye movements performed in three segregated zones of the screen, called as viewing areas, which restricted the range of eye movements in the form of twelve types of eye movements with different fixation positions. The viewing areas were determined by three different fixation positions and saccade movements in either horizontal or vertical direction. Therefore, left, middle and right viewing areas with the vertical (upward/downward) eye movements and top, middle and bottom viewing areas in the horizontal (rightward/leftward) eye movements can be investigated, separately. For specific validations of EOG influences, regression-based methods can be applied to EEG recordings with the reliable recording of additional EOG channels even if the number of EEG channels is moderate (Winkler et al. 2011). Also, it allows discuss on the effect directly using propagation coefficient values, which spreads over the head map, as the simplest way.

Our hypothesis is that EOG influence has a consistent difference according to conditions in viewing areas of the same eye-movement, due to the degree of the dipole orientation. Propagation coefficients in the linear regression obtained from the specific viewing area need to be applied to EEG data in the corresponding viewing area to improve the efficiency of the EOG artifact removal.

Methods and data analysis

In the systematic analyses of the EOG influence by extending the concept of Plchl et al. (2012), a possible influence of corneo-retinal dipole changes to the head map of the event-related brain potentials should be considered, as illustrated in Fig. 1. Even in the same kind of eyeball movements, such as in horizontal and vertical axes, different influences may occur depending on the viewing areas on the screen. In the present study, the linear regression method was used to make comparison between such different conditions and the analyses were performed separately in horizontal and vertical directions.

Fig. 1 Schematic illustration of corneo-retinal dipole changes depending on viewing areas. *Left* Condition of seeing the left side. *Right* Condition of seeing the center. *Contour lines* in *graded gray colors* represent a stationary influence of EOG at least lasting for 500 ms on the EEG instantaneous changes. The illustration explains the EOG influence that differs according to position of EEG channels depending on the dipole orientation and affects the baseline of EEG activities

Fig. 2 EOG and EEG channel locations in the head map. **a** EOG electrodes attached on the face with 7 channels. **b** 23 EEG channels attached on the scalp using the EEG cap based on the International 10–20 system. EEG electrodes are aligned in a line with 20 % of the inion-to-nasion distance (gray dashed lines). See also Fig. 12

Participants

EOGs were recorded using 7 electrodes surrounding eyes (Fig. 2a) and EEGs were recorded using 23 scalp electrodes (Fig. 2b) in the task with 12 different eye movement conditions (Fig. 3a). The EOGs and EEGs were obtained consistently from 8 subjects with the mean age of 26.1 years old (age range from 21 to 45 years old; 7 male and 1 female) and without any signs of medical or psychiatric illness. All the subjects with normal vision or with corrected-to-normal vision signed consent after being clearly informed of the purpose and procedures of the experiment. The experiment protocol was approved by the Ethics Committee in Future University Hakodate.

Stimuli and experimental procedure

The subjects sat in a comfortable arm chair in front of a 21-inch CRT monitor (Sony, CPD-G520, refresh rate

85 Hz, 1024 × 768 pixels). An ophthalmic chin rest was used to support the subject's head to prevent irregular head movements. All the subjects were instructed to stare at the fixation point on the screen and follow a target point with their eyes. The subjects were requested not to blink during each trial. To maximize the effect of the prevention of blinks, a 'my-pace' handy button was used to allow the subject decide their own starting timing during every trial. Stimuli were presented on a black background according to the software programmed in MATLAB (MathWorks, USA) with the Psychophysics Toolbox extensions (Brainard 1997).

During the experiment, as shown in Fig. 3, subjects performed horizontal and vertical eye movements according to the stimuli pattern. Eye movement range was consistently given as 12° in horizontal and vertical directions. Fixation points and eye movement directions were selected semi-randomly in the whole sessions and trials (Fig. 3b). As illustrated in Fig. 3c, after 'my-pace' button was pressed, the

Fig. 3 Task design and the scheduling. **a** Horizontal eye movement conditions were segregated into three viewing areas horizontally (*left*) and vertical eye movement conditions were segregated into three viewing areas vertically (*right*). **b** Presentation and timing to shift from the fixation, target and blank screen. **c** Task scheduling in the self-paced saccade eye movement

experimental system beeped to induce the subject to start the next trial. After 0.3 s, a fixation mark appeared in one of the six positions (Fig. 3a) by a circle with the bar (Fig. 3b) to represent the forthcoming eye movement's direction (either horizontal or vertical). The eye movement was cued to perform from the fixation mark to reach the target position shown by a circle without the bar. The subjects were instructed to gaze the target until the target was lost. The trial termination was noticed by the next beep. Therefore, the eyeball was expected to stay stationary for one second.

In the present study, twelve types of eye movement conditions were abbreviated by using notations of horizontal (H) for the first letter, top (T), middle (M) and bottom (D) for the next letter to represent the fixation positions, and leftward (L) or rightward (R) for the last letter to represent the eye movement directions in the horizontal case. In a similar manner, vertical (V) was the first letter, left-side (L), middle (M) and right-side (R) were the next letter for the fixation position and upward (U) or downward (D) was the last letter for the eye movement direction in the vertical case. Thus, abbreviations were given like HMR and VLU.

The whole experiment was divided into 4 sessions by rest breaks for subjects a few minutes each. In every session, each subject performed 13 trials under 12 conditions in a semi-random order and then 52 trials for every condition in total were recorded in this experiment.

EEG and EOG recording and data analyses

EEG and EOG signals were acquired by using a 32-channel BrainVision amplifier (BrainProducts, Germany) with 0.01–100 Hz bandpass filter with a sampling rate of 500 Hz. Ag/AgCl electrodes were used for all recording channels. 23 channels were used for EEGs according to the International 10–20 system (Fig. 2b), seven channels for EOGs (Fig. 2a) and two channels for reference electrodes located at earlobes. In EOG channels, five vertical EOG electrodes were placed on supraorbital and infraorbital rims of right and left eyes, which were labeled as VRu, VRd, VLu and VLd, and on the forehead approximately 25 mm above the nasion labeled as Vz. Two horizontal EOG electrodes labeled as HL and HR were placed on the left and right outer canthi. EEG recordings were referenced to an electrode between Fz and Cz during measurement and re-referenced to linked earlobes for data analyses. VEOG and HEOG were, respectively, defined as the average of vertical EOGs given by $[(VRu - VRd) + (VLu - VLd)]/2$ and the difference between horizontal EOG electrodes given by $HL - HR$.

In general, EEGs contain higher frequencies related to cognitive functions, such as *gamma* rhythm with frequencies higher than 30 Hz (Buzsáki 2011). It has been known that frequencies of signals from corneo-retinal dipole changes caused by eye movements are restricted in 4–20 Hz (Keren et al. 2010). Therefore, in the same manner as a conventional treatment in the ERP studies (Luck 2014), all EEG recordings were filtered by a 30 Hz FIR low pass filter before data analysis in the aim of investigation of the EOG influence on EEGs. In the ERP analysis of EOGs and EEGs, each onset was given by the time point of the highest inclination in the EOG change (Fig. 3c), which was calculated by the largest difference between the present time and past 10 ms, and set as $t = 0$. Then ERPs were obtained from –250 to 400 ms for every channel of EEGs and analyzed with EOGs. Bad trials were rejected by the following simple procedure based on statistical characteristics. The procedure was given as below:

1. Alignment (mean value removal): $s_i^{ch}(t) = e_i^{ch}(t) - \bar{e}_i^{ch}$ where $\bar{e}_i^{ch}$ was the mean value of the i th trial and ch represent 23 EEG channels and VEOG and HEOG. Aligned ERP signals $S_{trial}^{ch}(t) = [s_1^{ch}(t), s_2^{ch}(t), \dots, s_N^{ch}(t)]$

- (t)]($i = 1, \dots, N$) were obtained in each trial, where N is the number of trials.
2. Calculating the mean μ^{ch} and the standard deviation σ^{ch} over trials.
 3. Bad trial rejection: the proper data was defined as $S_{G_trial}^{ch}(t) = \{\forall t, |s_i^{ch}(t)| \leq \eta \cdot \sigma^{ch}(t)\}$ due to the assumption that an abnormal trial involves, at least, one data point exceeding the predefined threshold $\eta \cdot \sigma^{ch}(t)$. In this analysis, we used $\eta = 3$ for EOGs and $\eta = 4$ for EEGs as the bad trial rejection threshold. In the same trial, whichever the EOG or EEG exceeded the predefined threshold, the whole set of recorded data was removed from the analysis.

Linear regression method

In agreement with the previous researches (Croft and Barry 2000; Schlögl et al. 2007), the model of EEG and EOG can be described by a linear equation:

$$mEEG^{ch}(t) = rEEG^{ch}(t) + \sum_{i=1}^M mEOG_i(t) \times b_i^{ch} \quad (1)$$

where $mEEG$ represents measured EEG signals on the scalp, $rEEG$ represents the ‘real’ EEG signal, which is difficult to access due to artifacts contamination. In this formulation, three types of EOGs were assumed as three-dimensional directions, including vertical, horizontal and radial EOGs. Thus, $M = 3$. In the linear model, $mEOG_i$ and b_i represent the i -th EOG component and the corresponding propagation coefficient, respectively. Croft and Barry (2000) focused on the three EOG components for detailed ocular artifact corrections, while vertical and horizontal EOGs can be detected easily in saccade tasks and the radial component is too small to be detected in experiments (Schlögl et al. 2007; Thurtell et al. 2012). It suggests a possibility to improve the separation of EOG components that fits for the actual influence on EEGs.

In the present study, 12 eye movement directions were considered and individual influences were separately analyzed, as shown in Fig. 3a and the linear model was extended to give the task dependent regression as

$$rEEG_{***}^{ch} = mEEG_{***}^{ch} - mEOG_{***}^{ch} \times b_{***}^{ch} \quad (2)$$

where $***$ represents the task abbreviation defined in the above section, which is composed of letters to represent the axis, fixation position and movement direction, such as HMR and VLU.

For calculation of the propagation coefficients b_{***}^{ch} , Gratton-style procedure (Gratton et al. 1983) had been recognized as the major and traditional method. After that, the aligned-artifact average technique, called ‘AAA’ method,

was proposed by Croft and Barry (1998), and it is currently known as the single component regression analysis method.

In the AAA method, EEG and EOG were firstly aligned according to the predefined onset in the event, such as saccade, and then propagation coefficients were calculated from averaged EEGs and EOGs under the same condition through the linear regression using the Pearson product-moment correlation coefficient. Croft and Barry (1998) considered an effective removal of non-time-locked noise components in signals, which is eliminated by the aligned average of EEGs and EOGs, and demonstrated the better performance of the AAA method rather than results of the Gratton-style procedure (Croft and Barry 2000). In the present study, HEOG was used for $mEOG_{H**}$ in the horizontal case as H** and VEOG was used for $mEOG_{V**}$ in the vertical case as V**.

Results

EOG influences to EEG channels in vertical and horizontal eye movements

After elimination of the bad trials, the average number of trials bearing proper data under every condition in each subject was 37.8 (at least larger than 31). In the total number over all subjects, 72.7 % was the average ratio of the proper data, i.e. 302.5 trials under every condition from all 416 recorded data. In every 12 conditions, saccade ERPs of VEOG, HEOG and EEGs were analyzed as the averaged temporal sequence aligned to the onset timing from all proper trials under each condition. According to the definition of the ERP period as $[-250, 400 \text{ ms}]$, task dependent EOGs and examples of ERPs (FP1, F7, Fz and Cz) were shown in Fig. 4. In horizontal eye movements abbreviated as H** (Fig. 4a), which include leftward/rightward saccades, the HEOG changed positively in the case of leftward saccades (H*L) and negatively in the case of rightward saccades (H*R). After 50 ms from the onset, the averaged HEOGs stayed around $\pm 200 \mu\text{V}$ as a stationary influence on EEGs, which lasted 350 ms. In contrast, the VEOG changes were at a negligible level, representing that subjects properly performed without noticeable vertical eyeball rotations and eyelid movements. ERPs at EEG channels located close to the left eye position, such as FP1 and F7, were clearly affected by HEOG changes, while ERPs at electrodes on the midline, Fz and Cz, were basically flat throughout the period, indicating negligible influence from horizontal eye movements. F7 had the highest ERP amplitudes after the onset which was about $\pm 30 \mu\text{V}$, in leftward and rightward saccades, representing the largest EOG influence rather than others. In the temporal sequences, differences of ERPs depending on

Fig. 4 Temporal sequences of EOG and saccade ERP changes with respect to the onset timing. **a** Horizontal EOG as HEOG and vertical EOG as VEOG (top) and ERPs of FP1, F7, Fz and Cz channels (bottom) in horizontal eye movements. **b** HEOG and VEOG (top) and ERPs of FP1, F7, Fz and Cz channels (bottom) in vertical eye

movements. *Thick lines* represent data at the central fixation point and *thin and dashed lines* are at lateral fixation points. The *dashed line* represents the onset, which was defined by the time point of the maximum inclination of the temporal changes, practically

fixation points on top/middle/bottom (HT*, HM* and HD*) were not clearly exhibited. In vertical eye movements abbreviated as V** (Fig. 4b), which include upward/downward saccades, the VEOG changed positively in the case of upward saccades (V*U) and decreased negatively in the case of rightward saccades (V*D). In the upward VEOG, an overshoot of the upward VEOGs around 25 ms after the onset is presumed as a phenomenon when eyeballs drift upward and interact with eyelids, which is consistently observed in the result of Plöchl et al. (2012). In spite of the same vertical eyeball rotation of $\pm 12^\circ$, upward and downward VEOGs exhibited the different amount of amplitudes depending on electrode positions related to muscular structures around eyebrows and cheeks. In vertical cases, the four EEG channels showed influences from VEOGs on ERP changes as positive and negative amplitudes depending on upward and downward saccades, respectively. FP1 had the highest ERP amplitude about 50 μV after the onset in the upward saccade, which is also consistent with results reported by Plöchl et al. (2012) at fronto-central electrodes under the condition of 11.5° eyeball rotation. In other electrodes, such as F7, Fz and Cz, both positive and negative changes were observed consistently in upward and downward saccades.

movements. *Thick lines* represent data at the central fixation point and *thin and dashed lines* are at lateral fixation points. The *dashed line* represents the onset, which was defined by the time point of the maximum inclination of the temporal changes, practically

In comparison between horizontal and vertical eye movements, ERPs were affected by EOG influences differently depending on electrode positions of EEG channels. ERP at electrodes on the midline, such as Fz and Cz, had no EOG influences in horizontal eye movements and had non-negligible influences in the vertical eye movements. A tendency of the vertical symmetry in ERP amplitudes of the four electrodes in the vertical cases did not appear in the horizontal cases. These results indicate that EOG influences affect ERPs in horizontal and vertical eye movements in a different manner. It implies that the ERP topography analyses answer the question how the cornea-retinal dipole orientation impacts EEG channels.

ERP topographic patterns differentiate depending on eye movement direction and viewing area

As shown in Fig. 5, topographical maps of the ERP activity were analyzed as averaged potentials for 150–350 ms in the form of 2D contour maps ranging in $\pm 50 \mu\text{V}$. In horizontal eye movements of H**, contour patterns in the ERP topography of the same fixation position exhibited mirror images between opposite directions, for example, pairs of leftward and rightward directions, such as HTL versus HTR, HML versus HMR and HBL versus HBR. In comparison between

Fig. 5 Saccade ERP patterns in the head map depending on 12 conditions

different fixation positions, contour lines from the top-fixation topography (HTL or HTR) to the bottom (HBL or HBR) decreased in width especially in occipital areas, suggesting an extended EOG influence in the bottom-fixation case compared with the top. Such a difference does not seem to be recognized simply in the topographical representation, but the ERP activities of top and bottom fixations were significantly different [$t(df > 60)$; $p < 0.05$] in almost all channels [89 % (20.5 channels) in average], as shown in Fig. 6.

In vertical eye movements of V**, ERP topographies of the same fixation positions were different which demonstrated positive and negative values, respectively, in upward and downward eye movements in the same way as the way of ERP time courses (Fig. 4b). In comparison among conditions of three fixation positions, such as VL*, VM* and VR*, the contour lines were similar around EEG channels on the midline, but the gradient were different especially in lateral channels. The comparison between left and right fixation positions exhibited significant difference [$t(df > 60)$; $p < 0.05$] in channels of the left side (F7 and FC5) and right side (F8, FC6, T8 and C4) in the upward case (VLU-VRU in Fig. 6). In the same manner, left channels (F7, F3, FC5 and T7) and right channels (F8, F4, FC6 and T8) were significantly different in the downward case (VLD-VRD in Fig. 6). These results indicate that fixation position dependent EOG influences appear at the ERP topography of most channels in the horizontal cases, while such a difference localizes in

Fig. 6 Pairwise t test value over eight subjects on ERP in four distant pairs in the same direction. Channels with the significant difference [$t(df > 60)$; $p < 0.05$] are marked with a star

lateral areas in the vertical cases. Clearly, it suggests that central electrodes are similarly influenced by VEOG without the sensitivity to the viewing areas.

Direction and viewing area-sensitive propagation coefficients

The linear regression analysis was introduced as a tool to clarify how the EOG influence differs according to the

conditions in viewing areas and saccade directions, and what contribution can be obtained in improvements of EOG artifact corrections on the basis of considerations of its direction and viewing area-sensitivity. Figure 7 exhibited propagation coefficients in the regression model as formulated in Eq. 2 with respect to 12 conditions. Topographic patterns of the coefficients demonstrated consistent contour lines in the same manner as the ERP topographies (Fig. 5) except the sign (positive or negative) of the value. Figure 8 exhibited individual differences in neighboring pairs and distant pairs and marks on electrodes represent the significant difference in pairwise T test over 8 subjects. Under horizontal conditions of H*L and H*R, four neighboring pairs were established by comparing the top with middle fixation positions (T–M) and comparing the bottom with the middle fixation positions (B–M) in leftward and rightward directions. In the leftward direction (H*L), a positive peak was observed in neighboring pairs of T–M and B–M, which was located in opposite sides, and a negative peak was observed similarly in neighboring pairs of the rightward direction. The prominent difference appeared at distant pairs, such as comparisons of top and bottom fixation positions (T–B), and the number of electrodes with the significant difference [$t(7) > 3.499$; $p < 0.01$] was 65 % (15 channels) in average. Under vertical conditions, there were a few channels with the

significant difference in neighboring pairs and no clear difference in the distant pair, particularly in the upward direction (V*U), while clear differences were observed in lateral channels in the downward direction (V*D), which in a similar manner as ERP differences.

To evaluate the EOG artifact correction using the specificity of viewing areas and eye movement direction as we focused in this work, the leave-one-out cross-validation method was introduced. Under each condition, by using the N proper dataset, propagation coefficients of the linear regression were calculated from the $N - 1$ dataset and applied to the trial left out. Depending on which trial was left, results of N sets was obtained and then they were used to validate how much EOG influence remains in EEG data after the artifact correction. By connecting corrected N EEG time series in a successive manner and N corresponding EOG time series in the same way, a single value of the correlation coefficient (CC) was calculated by the two time series of the connected N -corrected EEG and the corresponding EOG time series. Therefore, the CC can be used for a measure to evaluate how much EOG influence remains, varying from 0 to 1. Thus, 0 and 1 respectively represent no correlation between corrected EEG and EOG and a high correlation between them. We defined ‘proposed method’ as the result of the leave-one-out cross-validation and ‘normal method’ as the consistent procedure applied to

Fig. 7 Propagation coefficient distributions in the head map depending on 12 conditions

Fig. 8 Topographic maps of coefficient difference classified by four groups of horizontal/vertical condition and two alternative directions. *Top block* In the horizontal case, T–M and B–M denote neighboring pairs of top versus middle fixation positions and bottom versus middle fixation positions respectively, and T–B denotes the distant pair of top versus bottom fixation positions. *Bottom block* In the vertical case, L–

M and R–M denote neighboring pairs of left versus middle fixation positions and right versus middle fixation positions respectively, and L–R denotes the distant pair of left versus right fixation positions. Channels with the significant difference [$t(7) > 3.499$; $p < 0.01$] are marked with a star

the same target EEG signal, but using propagation coefficients obtained from the dataset of the center fixation condition. In every channel and each condition, we finally obtained individual CC from the corrected EEG with the EOG in the proposed method and individual CC for the normal method correspondingly. In other words, the proposed method means EEG corrections calibrated with data of task-sensitive fixation positions. In comparison between the proposed and normal methods, the pairwise t test over 8 subjects was analyzed after the Fisher's Z-transformation of two sets of CCs for subjects. Figures 9 and 10 exhibited an averaged CC (inversed Z-value) over all subjects in every EEG channel in cases of horizontal and vertical conditions, respectively. The figure was highlighted by gray background colors representing ERP absolute amplitudes in corresponding channels as shown in Fig. 5. Under horizontal conditions, the significant difference between proposed and normal methods appeared at lateral 14

channels in leftward eye movements and 21 channels in rightward eye movements [$t(7) > 3.499$; $p < 0.01$]. In comparison between two methods, the difference of CC values in those channels was about 0.1 in average (0.099 in HTL&HBL and 0.093 in HTR&HBR), which can be estimated as 10 % of the EOG influence, such as $\pm 5 \mu V$ in EEG signals if the maximum range of the EOG influence is $\pm 50 \mu V$. In the same manner, under vertical conditions, the significant difference appeared in 12 channels distributed from parietal to occipital areas in the case of upward eye movements, whereas lateral 12 channels distributed from frontal to parietal areas in the case of downward eye movements. The difference of CC values in those channels was about 0.08 (0.071 in VLU&VRU and 0.093 in VLD&VRD) because of relatively weak differences in the upward case.

These results indicate that fixation position dependent EOG influences are exhibited at propagation coefficients

Fig. 9 Correlation coefficient (CC) values between EOG and EEG after the artifact correction of the linear regression method under the leave-one-out cross validation test in the horizontal case. ‘Proposed’ represents the result of the leave-one-out cross-validation, which propagation coefficients from the $N - 1$ dataset in individual conditions and applied to the trial left out. ‘Normal’ represents the consistent procedure applying to the same target EEG signal but using

propagation coefficients obtained from the dataset of the center fixation condition. Plots were only connected according to the line of the International 10–20 systems (Fig. 2b) and highlighted by *gray background colors* represent ERP absolute amplitudes in corresponding channels (Fig. 5) to compare the original EOG influences. Channels with the significant difference [$t(7) > 3.499$; $p < 0.01$] are marked with a *star*

Fig. 10 Correlation coefficient (CC) values between EOG and EEG after the artifact correction of the linear regression method under the leave-one-out cross validation test in the vertical case, which were obtained in the same procedure in Fig. 9

and then the cross-validation based evaluation represents an improvement of the traditional method when the proposed concept is applied to the EEG artifact correction. In

the case of the linear regression by using the proposed method, 10 % accuracy improvements can be estimated in areas including channels marked in Fig. 11.

Fig. 11 Pairwise t test value over eight subjects on propagation coefficients between ‘proposed’ and ‘normal’ defined in Fig. 10. Channels with the significant difference [$t(7) > 3.499$; $p < 0.01$] are marked with a star

Discussion

The aim of the present study is to clarify the EOG influence on EEG measurements with respect to changes of eye movement directions and fixation positions in the saccade task. In the proposed self-paced fixation-and-saccades task with twelve conditions, EOG influences were differentiated in individual EEG channels yet the mechanism and further potentials for the artifact removal are needed to consider as below.

Eye movement specificity in the EOG generation

With respect to the morphology of eyeballs and extraocular muscles with nervous controls, eye movement kinematics were modeled with horizontal, vertical and radial (torsional) axes properties in a gain control model (Haslwanter et al. 2000). In the three-dimensional kinematics of saccade eye movements, eye movement trajectories were projected mostly to a horizontal-vertical plane with less variation in torsional axis (Thurtell et al. 2012). The amplitude of the internal cornea-retinal potential was estimated in a range of 10–30 mV (Marmor and Zrenner 1993; Ding et al. 2005) and the potential was recorded as less than 1 mV using the skin-surface electrode as the EOG recording tool (Dorf 2003; Shinomiya et al. 2008). The millivolt range of EOGs caused a large impact on EEG signals as the dominant noise source (Berg and Scherg 1991; Croft and Barry 2000;

Picton et al. 2000; Schlögl et al. 2007). The eye movement angle was linearly correlated with a sustained EOG potential if it is in a specific range, such as less than 30°–40° (Shinomiya et al. 2008), whereas the potential fluctuation caused by saccades had a dynamic property according to interaction with eyelids (Bour et al. 2000; VanderWerf et al. 2003). For a simple and phenomenological treatment, the influence of EOGs traditionally were treated by a 3D dipole model of eye movement (Croft and Barry 2000; Picton et al. 2000; Schlögl et al. 2007), or removed by using multiple EOG channels to enhance the ICA accuracy (Joyce et al. 2004). According to the comparison between the ICA-based correction and regression-based correction with two spatial components, they had a similar performance in frontal channels but different performance in parietal and occipital channels (Plöchl et al. 2012). The ICA based correction removes artifacts from corneo-retinal dipole changes with less dependency on channel locations, suggesting that the regression-based method needs to include an accurate model of how the EOG influence expands over the head map for an improved performance. In addition, Plöchl et al. (2012) applied ICA to microsaccade-related artifacts, which was not simply concluded about the effectiveness with respect to regression methods.

Possible improvements in other artifact correction methods

Regression methods provides a straightforward way for removing eye movement related artifacts. The simple calculation allows artifacts to be reduced from EEG signals with less computational cost but some difficulties remain unsolved. For example, the regression has problem with the simultaneous artifact removal of the corneo-retinal dipole and eyelid interactions (Plöchl et al. 2012). Currently, ICA is the most popular method treating for artifact corrections (Urigüen and Garcia-Zapirain 2015), which provides a way to basically remove various types of artifacts in the off-line calculation after all the recording of the EEG time series. Theoretically, ICA solves many difficulties in the regression method and has been widely-applied to eye-movement related ERP (Jung et al. 2000), whereas the effectiveness of the ICA strongly depends on the quality of the signal decomposition (Plöchl et al. 2012). Lau (2012) tested the quality of EEG decompositions by using a recording system with 256 channels and demonstrated the decomposed signal correlation in the comparison of sets from 115 to 25 selected channels. In their result, the correlation gradually changed from 115 to 35 channels, while there was a gap between 35 and 25 channels, suggesting a less confidence in the ICA decomposition of EEGs since the number of channels was fewer than 35 channels. This fact indicates

that ICA cannot be simply applied to simplified online BCI systems for a mobile use with a small number of channels.

As another relationship between ICA and the identification of types of eye movements, Plöchl et al. (2012) proposed an effective objective procedure to remove independent components (ICs) that are identified as eye artifact-related components by using the threshold value defined by the saccade/fixation variance ratio obtained by the eye-tracking system. Originally, the removal of the eye movement-related ICs is relying on subjective judgments through visual inspections by expert researchers in the intermediate phase between the ICA decomposition and recombination, whereas they proved that the detail characteristics of eye movements helped to improve ICA approaches. Not only the results in this study do not simply contribute to ICA improvements, but the finding of direction and viewing the area-sensitive influence of EOG artifacts may help the classification of ICs in a similar manner.

Further extended approaches to focus on non-stationary properties in the signal have been proposed. Feature subset selection method based on the sequential forward floating search algorithm (Zhang et al. 2015) promoted the accuracy in single-trial classification of mental states beyond traditional trial-averaged analysis, and stochastic event synchrony method could be applied to single-trial synchrony of steady-state visual evoked potentials (Vialatte et al. 2009). Those studies are oriented in the same direction as the present study in the sense of the importance of online EEG analyses. Recurrence quantification analysis applied to the ERP analysis (Schinkel et al. 2007) is available to extract the event of interest automatically according to the signal characteristics in time course. It helps online EEG analysis if the signal “onset” is unclear. We defined the onset in the saccade task procedure simply, whereas the detection of transitions of fixations and saccades is necessary for the application to the free-viewing condition.

Electrophysiological aspect of the zone-of-gaze sensitivity in the artifact correction

In this experiment, we used the International 10–20 system for the alignment of EEG channels over the head (Fig. 12), which is the international standard for EEG recordings. In electrophysiological and morphological aspects of the corneo-retinal dipole, the dipole is capable of producing the basement change of EEG potentials. Depending on the dipole orientation horizontally and vertically, individual EEG channels were influenced with different amplitudes as we demonstrated in ERP time courses (Fig. 4) and the topography (Fig. 5). In general, adaptive filter methods have been proposed for the ocular artifact removal

Fig. 12 EEG channel distributions according to the International 10–20 system over the head, and estimated vertical orientations of the corneo-retinal dipoles in the present study. EOG influences are varied depending on the dipole orientation

(Georgiadis et al. 2005; Sanei and Chambers 2007; Gentili et al. 2010) to remove noise from a time-varying signal. He et al. (2004) formulated an adaptive filter under the consideration of two components of VEOG and HEOG. Instead of the time-varying aspect, spatially-varying information is an important factor to improve artifact removal. As Plöchl et al. (2012) preliminary reported, the saccade size, or a length from the fixation position to the target, do not display significant differences, but the directional changes, such as comparison of opposite directions, produce the differences. In the present study, the result showed significant differences depending on fixation positions extendedly, which we analyzed as viewing areas. As demonstrated in Fig. 8, propagation coefficient values of L–M and R–M tend to be significant in the posterior area under the V*U condition, while they tend to be significant at the frontal area under the V*D condition. Plöchl et al. (2012) discussed this point by exhibiting significantly larger ERP values of downward saccades rather than upward saccades from parietal to occipital channels. A considerable mechanism is that EOG influences reach individual EEG channels effectively depending on the orientation. Indeed, the standard EEG propagation is essentially instantaneous. EOG influences have a time limitation for the interference occurred on EEGs. According to the facts, we designed a systematic saccade task with the combination of fixation positions and directions and set the time duration of one second for fixations at the start and end, which can be expected to keep the same ocular potential more than 500 ms. In the free-viewing task with various types of scenes, Kaspar et al. (2011) investigated the nature of saccade behaviors. They reported that mean saccades

duration is about 300 ms in the case of natural sciences and it increases gradually from novel to familiar conditions. Therefore, our task design fits for natural conditions and the results can apply to the free-viewing task, which has a large expectation in BCI studies. Recently eye-tracker systems are getting to be accurate with a high sampling rate to be able to compare with EEG measurements. The combination of ICA and the eye-tracker to compensate EOG information, which is enhanced by 12 type saccades that we designed, has a large potential in the calibration of EEG artifact corrections as is discussed by Ai et al. (2016).

Future directions of the EEG studies focus on investigating higher cognitive functions in daily life, including analyses of the language processing by using ERP components of P1 and N1 (150–200 ms post-stimulus onset), P2 and N2 (200–300 ms) (Malaia and Newman 2015), the conscious stage based on the sensory-motor attention processing with more longer period until 500–600 ms, which involves the P3 component (Taylor 2007). We designed a systematic task with 12 type eye movements in the purpose of the investigation of EOG influences. It will be extended to investigations of the interference depending on the periods defined by ERP components related to the cognitive processes.

Conclusion

In the present study, we hypothesized the existence of direction and viewing area-sensitive EOG influence in the EEG topographic pattern and investigated the influence of eye movement-related artifacts in the direction/viewing area depending saccade task. This was evaluated using the systematic protocol to evaluate the dependency on the coupling effect of eye-movement direction and viewing area and testified in the framework of the linear regression analysis for EOG corrections. In our experimental results, ERP topographic patterns to evaluate EOG influences in the EEG head map showed significant differences in most of the channels in the comparison between top and bottom fixation positions under horizontal eye movements and in lateral channels in the comparison between left and right fixation positions under vertical eye movements. In the analysis by using the linear model, propagation coefficients showed significant differences consistently, and the cross-validation analysis demonstrated possible improvements with a 10 % better performance rather than traditional methods based on the single center fixation position. The result will contribute to free viewing EEG tasks, including saccades with various eye movement directions.

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