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Assessing the effects of voluntary and involuntary eyeblinks in independent components of electroencephalogram

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ABSTRACT

The effect of voluntary and involuntary eyeblinks in independent components (ICs) contributing to electroencephalographic (EEG) signals was assessed to create templates for eyeblink artifact rejection from EEG signals with small number of electrodes. Fourteen EEG and one vertical electrooculographic signals were recorded for twenty subjects during experiments that prompted subjects to blink voluntarily and involuntarily. Wavelet-enhanced independent component analysis with two markers was employed as a feature extraction scheme to investigate the effects of eyeblinks in ICs of EEG signals. Extracted features were separated into epochs and analyzed. This paper presents following characteristics: (i) voluntary and involuntary eyeblink features obtained from all channels present significant differences in the delta band; (ii) distorting effects have continued influence for 3.0–4.0 s (in the occipital region, 2.0 s); and (iii) eyeblink effects cease to exist after the zero-crossing four (in the occipital region, two) times, regardless of the type. Several characteristics are different between voluntary and involuntary eyeblinks in EEG signals. Therefore, any templates need both types of data for eyeblink artifact rejection if the EEG signals were obtained from small number of electrodes.

1. Introduction

Kaleidoscopic functional states of the cerebral cortex affected by neuronal activities (nerve firings) can be measured using an electrical non-invasive index, in the form of an electroencephalographic (EEG) signal. The EEG signal is the useful clinical tool for the diagnosis of psychiatric disorders such as schizophrenia and epilepsy, and for studying the functional states of the brain [1,2]. In addition, EEG signals have been widely used in brain-computer interface (BCI) systems that provide communication channels to people with severe motor disabilities [3,4]. Over the past three decades, the spatio-temporal event-related neural dynamics revealed from various experimentally manipulated events and interpretation of EEG signals have been developed to integrate dynamics with practical applications.

The good conductivity of the scalp leads to contamination of recorded EEG signals with potentials generated from movement of the eyelid and/or the eyeball, which may affect on delta (0.5–4.0 Hz), theta (4.0–8.0 Hz), and alpha (8.0–13.0 Hz) bands [5,6]. Eyeblink artifacts are extremely burdensome when investigating neuronal activities using EEG signals because the EEG spectrum is superimposed with the artifacts [7]. Furthermore, the amount of oscillating neuronal discharge (EEG potential) is generally lower than the artifact potential at each electrode [8]. The effects of eyeblinks on EEG signals depend on the orientation of the eyeball, the trajectory of the eyelid, the location of the electrode on the scalp, and the propagation path of the electric field across the head [9,10]. Although researchers are able to avoid the issue by giving an instruction that asks subjects to keep their eyes closed during the EEG measurement, any constructed system based on the research would be impractical in the real world because of the necessity of having users close their eyes while the system operates. In addition, the inhibition of eye movements or eyeblinks significantly distorts the neuronal activity [11]. Therefore, EEG signals should be recorded with the eyes open and without any constraints to allow investigation into intrinsic endogenous brain activities, even if the eyeblink artifactual contamination of the EEG signal cannot be avoided because of the structure of human body.

Regression-based approaches include the well-known ocular artifact removal method for investigating plausible neuronal activities with the eyes open [12]. In this approach, propagation factors are calculated using linear least-square regression to estimate the relationship between the recorded electrooculographic (EOG) signals and the recorded EEG signals of each channel [13]. By subtracting the eyeblink artifact coordinated by the propagation factors, regression procedures remove eyeblink artifacts from each channel at a low computational cost. However, eyeblinks vary

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their amplitudes and durations according to the movement of the eyelid [14] and whether the blink occurs under voluntary or involuntary control [8,15]. For this property, the approximation performance of linear regression depends on the distribution of eyeblink amplitude and duration in the data set [16]. Furthermore, bidirectional contamination between EEG and EOG signals has been revealed; therefore, relevant cerebral information interfered with the EOG signal would also be canceled in the EEG signal corrected using a regression-based approach [17].

Eyeblink artifacts observed in EEG signals have the following properties: (i) the influence of the artifact is attenuated with increasing distance from the eyes [18]; and (ii) the activity of the artifacts appears to propagate along the anterior–posterior axis in a symmetrical fashion [5,8]. On the basis of these properties, theoretically multivariate statistical analysis approaches such as principal component analysis and independent component analysis (ICA), which separate EEG signals into spatially and temporally distinguishable components, are useful for extracting EEG components from the scalp recordings [19,20]. In particular, ICA is a powerful tool for separating the recorded EEG signals into maximally independent activity patterns derived from cerebral or non-cerebral (artifactual) sources [21]. ICA-based approaches have shown an extraordinary ability to solve blind source separation problems using the assumption of independence among signal sources in each subject's data. These approaches have been used in a wide range of EEG signal processing procedures for the removal of eyeblink artifact components from recorded EEG signals [22] and the extraction of signals of interest to improve the overall performance [23], regardless of the distribution of blink amplitude and duration. In comparison with the regression-based approach, the ICA-based approach accurately eliminates eyeblink artifacts from EEG signals with less loss of cerebral information [24].

A smaller number of electrodes (i.e., the single-electrode case would be an extreme case) should result in better practical applications in daily life. Single-channel ICA, which is an adaptation of ICA to single-channel signals, has been proposed [25]; however, the scheme does not always satisfy its assumptions in real-world applications. Therefore, proposing an eyeblink artifact removal scheme for a single-channel EEG signal is now a major challenge within EEG signal processing [26,27]. To avoid an inconsistency in separating components of a single-channel EEG signal that has overlapping frequency components, reference data helps experimental data to converge to the values of estimated sources in the aforementioned schemes. In addition, the presence of involuntary eyeblink artifacts in the target signal leads to a distorted signal after applying the reference-based scheme, because the reference is usually based only on voluntary eyeblink data. Although several research has analyzed the pattern of eyeblink artifacts to develop eyeblink artifact removal methods for multichannel EEG signals, the effect of involuntary eyeblinks on scalp EEG signals is still missing [22,28]. This study investigates the plausible effects of voluntary and involuntary eyeblinks on scalp EEG signals using multichannel ICA. Since recent studies have suggested wavelet-enhanced ICA algorithm is suitable for separating EEG signals into cerebral and non-cerebral sources [29], this study employed this method. Investigation of eyeblink artifacts under voluntary and involuntary control lead to development of more robust and more common references or training datasets based on the representative attributes for small number of channels in EEG analysis. Therefore, the objective of this paper is to characterize the effects of voluntary and involuntary eyeblinks on independent components (ICs) contributing to EEG signals by wavelet-enhanced ICA to create templates for eyeblink artifact rejection from a recorded EEG signal with a single-electrode.

2. Materials and methods

2.1. EEG and EOG recordings

In this paper, EEG signals were recorded at 14 positions (Fp1, Fp2, F3, F4, T3, C3, Cz, C4, T4, P3, Pz, P4, O1, and O2) according to the 10–20 system. Active electrodes for EEG data were made of sintered Ag/Ag–Cl material (g.tec Medical Engineering GmbH, Austria) and their metallic tips were attached to the scalp. A vertical EOG signal was recorded from two surface Ag/Ag–Cl electrodes (Blue Sensor P, Ambu Corp., Denmark) placed at the superior and inferior orbital rims of the left eye. Reference and ground electrodes were placed at the left mastoid and Fz, respectively. The EEG and EOG data were band-pass filtered from 0.5 Hz to 60 Hz with a Butterworth filter and digitized at a sampling rate of 256 Hz using g.USBamp. The first 5 s of recorded data is discarded. All electrodes were pasted with an electrolyte, g. GAMMAgel, to reduce skin resistance.

Twenty subjects (14 males and 6 females, mean age: 22.75 ± 1.45 years, 14 right and 6 left eye dominants) participated in the experiments. No subjects had a history of sensorimotor, ophthalmologic, or auditory abnormalities. All subjects were asked to read and sign an informed consent approved by the Research Ethics Committee of Keio University prior to participating the study. None of the subjects were permitted to wear eyeglasses and all used canal-type earphones during the experiments.

2.2. Stimuli and procedure

Each subject was seated in a dim room (mean illuminance: 188.95 ± 24.50 lx) in front of a laptop PC. The distance between subject and display was roughly 60 cm and the third highest lightness-contrast was selected, while displaying a cross-fixation on the display. During the experiments, the subject's face was video recorded using a tablet PC fixed to the frame of the monitor. The experimental procedure was written in Matlab using the Psychophysics Toolbox extensions [30], as follows.

2.2.1. Exp. 1 (for voluntary eyeblink)

An audio file (Windows Background.wav, 55.0 dB), which is used as an alert sound (a beep) in the Windows 8.1 operating system was used to obtain voluntary eyeblink data. The task is simply to focus on a black cross-fixation in the center of the display and to blink with both eyes within 1 s after the sound stimulus (see Fig. 1(A)). The simple auditory stimulus was repeated for this experiment to avoid interference with other eye-related potentials: (i) the occipital positive potential (the lambda wave) that is an evoked potential based on the changed visual stimulus, which typically occurs roughly 300 ms after the onset of a blink [31]; (ii) the cerebral potential caused by the efference copy, which represents a process for anticipation of the change in the visual stimulus from the eye-movement [32]. In each of the experiments, the subject was instructed to blink naturally, in addition to the prescribed blinks, and not to blink stiffly or strongly, but instead, to simply react quickly. The datasets for each subject consist of 3 sessions. Each session includes 20 trials; the next session is started after a 60-s resting period to maintain ocular moisture. Whereas normal adults blink every 3.0 s, a sound was presented every 5.0 or 6.0 s in a randomized order. In short, subjects had to blink in a slightly unusual way. However, the presentation interval was deliberately decided (as mentioned above) because we experimentally found that the effects of eyeblink on EEG signals have continued their influence for 3.0–4.0 s.