Analysis on EEG Signals in Visually and Auditorily Guided Saccade Task by FICAR

Arao Funase[1,2], Yagi Tohru[3,4], Motoaki Mouri[1], Allan K. Barros[5], Andrzej Cichocki[2], and Ichi Takumi[1]

[1] Graduate School of Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, 466-8555, Japan
[2] Brain Science Institute, RIKEN, 2-1, Hirosawa, Wako, 351-0198, Japan
[3] Graduate School of Information Science and Engineering, Tokyo Institute of Technology, 1-12-1, Ookayama, Meguro-ku, Tokyo, 152-8555, Japan
[4] Bio-Mimetic Control Research Center, RIKEN 2271-130, Anagahora, Shimoshidami, Moriyama-ku, Nagoya, 463-0003, Japan
[5] Technological Center, Universidade Federal do Maranhão, Rua dos Guriatans, Qd. 5, casa 22, Renascenca II, Sao Luis, MA, 65075000, Brazil

Abstract. Recently an independent component analysis (ICA) becomes powerful tools to processing bio-signals. In our studies, the ICA is applied to processing on saccade-related EEG signals in order to predict saccadic eye movements because an ensemble averaging, which is a conventional processing method of EEG signals, is not suitable for real-time processing. We have already detected saccade-related independent components (ICs) by ICA. However, features of saccade-related EEG signals and saccade-related ICs were not compared. In this paper, saccade-related EEG signals and saccade-related ICs in visually and auditorily guided saccade task are compared in the point of the latency between starting time of a saccade and time when a saccade-related EEG signal or an IC has maximum value and in the point of the peak scale where a saccade-related EEG signal or an IC has maximum value.

1 Background

Nowadays, many researchers have been researching "Brain Computer Interfaces (BCIs)". BCIs connect computers and human by EEG signals. BCIs have some advantages compared with conventional interfaces. First is that users do not use inputs with body movements but use inputs with thinking, emotion, and motivation. Second is that computers work before user's movements because EEG signals include information for predicting beginning time of user's movement.

The BCI, which is introduced by our group, predict eye movements by EEG signal before eye movements and move a mouse cursor by the EEG signal before eye movements. This BCI can improve the latency between beginning time of eye movements and beginning time of working system. Therefore, this advantage of our BCI is attractive for the alarm of inattentive driving and the high-speed targeting system. In conventional research, a saccade-related EEG was detected

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before eye movements by ensemble averaging method [1]. However, ensemble averaging method has a disadvantage because ensemble averaging method needs many repetitive trials. Therefore independent component analysis (ICA) method was applied to analysis on saccade-related EEG signals because the ICA method can process raw EEG signals and find indepedent components (ICs) related to various EEG activities.

In our previous research, the ICA method can extract saccade-related independent components [2]. However, saccade-related ICs were extracted in case of visually guided saccade task. Therefore, in this paper, we confirm whether saccade-related ICs can be extracted in case of auditorily guided saccade task and compare saccade-related ICs in case of auditorily guided saccade task with saccade-related ICs in case of visually guided saccade task.

2 Fast ICA with Reference Signal [3]

Recently, the ICA method has been introduced in the field of bio-signal processing as a promising technique for separating independent sources [4]. The ICA is based on the following principle. Assuming that the original (or source) signals are mutual independent and have been linearly mixed, and that these mixed signals are available, the ICA finds in a blind manner a linear combination of the mixed signals which recovers the original source signals, possibly re-scaled and randomly arranged in the outputs.

The $\mathbf{s} = [s_1, s_2, \cdots, s_n]^{\mathrm{T}}$ means n independent signals from EEG sources in the brain, for example. The mixed signals (or the recorded signals) $\mathbf{x}$ are thus given by $\mathbf{x} = \mathbf{A}\mathbf{s}$, where $\mathbf{A}$ is an $n \times n$ invertible matrix. $\mathbf{A}$ is the matrix for mixing independent signals. In the ICA, only $\mathbf{x}$ is observed. The value for $\mathbf{s}$ is calculate by $\mathbf{s} = \mathbf{W}\mathbf{x}$ ($\mathbf{W} = \mathbf{A}^{-1}$). However, it is impossible to calculate $\mathbf{A}^{-1}$ algebraically because information for $\mathbf{A}$ and $\mathbf{s}$ is not already known. Therefore, in the ICA algorithm, $\mathbf{W}$ is estimated non-algebraically. In order to calculate $\mathbf{W}$, the assumption of the ICA algorithm that $\mathbf{s}$ is mutually independent is used. Different cost functions, which are defined from the assumption, are used in the literature, usually involving a non-linearity that shapes the probability destiny function of the source signals. However, high-order statistics, such as the kurtosis, are widely used as well. The kurtosis shows how independent a signal is because the kurtosis is the classical measure of non-gaussianity. The Fast ICA which is one of the ICA algorithms, is based on a cost function minimization or maximization that is a function of the kurtosis $\kappa(\mathbf{w}^{\mathrm{T}}\mathbf{x}) = \boldsymbol{E}(\mathbf{w}^{\mathrm{T}}\mathbf{x})^4 - 3[\boldsymbol{E}\{\mathbf{w}^{\mathrm{T}}\mathbf{x}\}^2]^2 = \boldsymbol{E}\{(\mathbf{w}^{\mathrm{T}}\mathbf{x})^4\} - 3||\mathbf{w}||^4$; $\mathbf{w}$ is one of the raw of $\mathbf{W}$. Then Fast ICA changes the weight $\mathbf{w}$ to extract an IC with the fixed-point algorithm.

From among several ICA algorithms, we selected the "Modified Fast ICA with Reference signal (FICAR)" algorithm to use in this study [3]. This algorithm can extract only the desired components by initializing the algorithm with prior information on the signal of interest. The main advantage of this approach is users can give instructions to extract a desired signal more strongly.

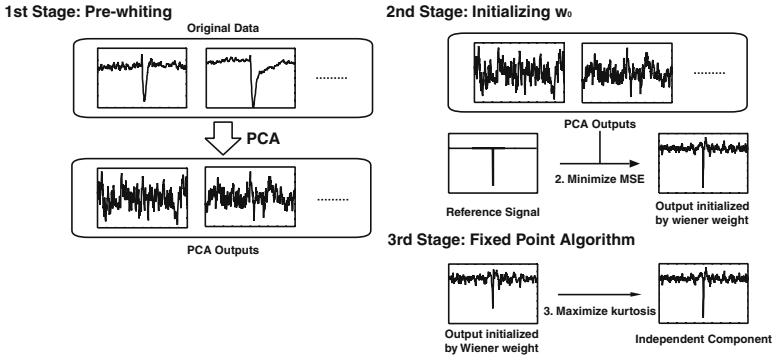

Fig. 1. Conceptual three stage for extraction of desired ICs

Fig.1 shows an overview of the procedures of FICAR algorithm. First, principal component analysis (PCA) outputs are calculated from original recorded signals to speed up the convergence of the algorithm. Second, this algorithm initialized $\mathbf{w}_k$ ($k = 0$; k is the iteration number.) using some priori information included in a reference signal, $\mathbf{d}$, correlated with $\mathbf{s}_i$, i.e. $\boldsymbol{E}[\mathbf{d}s_i] \neq 0$. This algorithm estimates a weight vector $\mathbf{w}$. Therefore, we calculate the error ε between $\mathbf{d}$, which is a reference signal, and $\mathbf{u} = \mathbf{w}^{\mathrm{T}}\mathbf{x}$; $\varepsilon = \mathbf{d} - \mathbf{u}$. The initial weight $\mathbf{w}_0$ are calculate by the minimization of the mean-squared error (MSE) given by $\boldsymbol{E}[\varepsilon^2]$. To calculate the MSE, the least mean square (LMS) is used in order to calculate the MSE. After some calculations, the optimum weight (also called the Wiener weight) to minimize the MSE was found to be $\mathbf{w}^* = \boldsymbol{E}[\mathbf{dx}]$. This algorithm initialized $\mathbf{w}_0 = \boldsymbol{E}[\mathbf{dx}]/||\boldsymbol{E}[\mathbf{dx}]||$. Third, this algorithm calculates $\mathbf{w}_{k+1}$ by $\mathbf{w}_{k+1} = \boldsymbol{E}[\mathbf{x}(\mathbf{w}_k^{\mathrm{T}}\mathbf{x})^3] - 3\mathbf{w}$ to maximize kurtosis. Then this algorithm can extract an IC closest to a reference signal or strictly speaking an IC which is correlated with the reference signal.

3 Experimental Settings

There are four tasks in this study. The first task is to record EEG signals during a saccade to a visual target that is on his right side or left side. The second task is to record EEG signals as a control condition when a subject dose not perform a saccade even though a visual stimulus has been displayed. First task and second task are called visual experiments. On the other hand, the third task is to record EEG signals during a saccade to a auditory target that is on his right side or left side. The fourth task is to record EEG signals as a control condition against the third task when a subject dose not perform a saccade even if a auditory stimulus has been turned on. The third task and fourth task are called auditory experiments. Each experiment is comprised of 50 trials in total: 25 trials on the right side and 25 trials on the left side.

The EEG signals are recorded through 19 electrodes (Ag-AgCl), which are placed on a subject's head in accord with the international 10-20 electrode po-

sition system. The electrooculogram (EOG) signals are simultaneously recorded through two pairs of electrodes (Ag-AgCl) attached to the top-bottom side and right-left side of the right eye.The number of subjects is five (Subject A, B, C, D, E). All subjects are men and have normal vision. All subjects are right-handed. All data are smpled at 1000[Hz], and stored on a hard disk for off-line data processing after post-amplification.

In this paper, the shape of the reference signal is that of an impulse signal having one peak. This shape is caused for two reasons. First, the saccade-related EEG had a sharp change like am impulse [1]. Second, the main components of an EEG signal are the neural responses, and the waveform of the neural responses is resembled to impulse.

4 Experimental Results and Discussion

4.1 Results of Ensemble Averaging

Fig.2 shows the experimental results obtained for "Subject A" when the visual stimulus on the right side is illuminated. This EEG data is processed with ensemble averaging and high-pass filter (cut-off 4 [Hz]). Fig.2-a and 2-b show the data with and without eye movement to right side, respectively. Black lines indicate results in visual experiments and gray lines represent results in auditory experiments. The top boxes show the voltage generated in response to the LED becoming illuminated. The middle boxes indicate the potential of EOG signals. The increase of EOG signals means an eye movement to right side. The bottom boxes represent EEG potential recorded at the right occipital lobe (at O2 in the international 10-20 electrode position system). The horizontal axes indicate the time span, where 0 [ms] indicates the start point of the eye movement. The

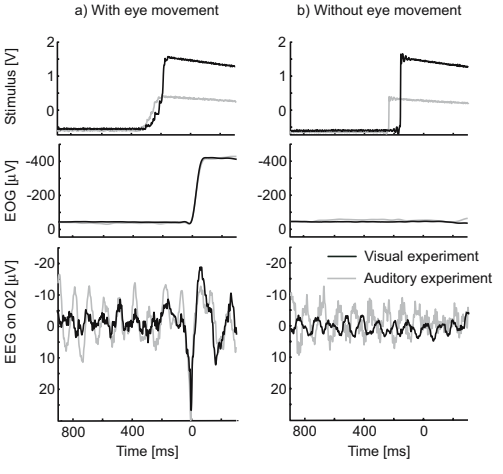

Fig. 2. Saccade-related EEG recorded on O2

Table 1. Peak time and amplitude on sharp change of EEG

	In visual experiments		In auditory experiments	
	Peak time [ms]	$n = \frac{\bar{x}-\mu}{s}$	Peak time [ms]	$n = \frac{\bar{x}-\mu}{s}$
	Right/Left	Right/Left	Right/Leftt	Right/Left
A	-3 / -2	8.6 / 9.3	-4 / -4	6.3 / 7.0
B	-5 / -3	6.3 / 7.8	-6 / -2	4.4 / 4.7
C	-3 / -4	7.0 / 6.9	-4 / -4	6.3 / 7.0
D	-3 / -2	8.2 / 8.2	-3 / -3	8.0 / 6.7
E	-3 / -3	7.8 / 7.9	-4 / -5	6.5 / 7.3
Ave.	-3.4 / -2.8	7.6 / 8.0	-4.2 / -3.6	6.3 / 6.5
STD	0.9 / 0.8	0.9 / 0.9	1.1 / 1.1	1.3 / 1.1

amplitude of the EEG signal is sharply changed just before eye movement in the case of an eye movement. However, there was no change for the case of no eye movement. The same tendency was observed for all five subjects in the case of both visual and auditory experiments.

In order to focus on features of saccade-related EEG signal, a time when saccade-related EEG signals have maximum amplitude and maximum amplitude is checked in Table 1. Amplitude was defined as n which is how many times standard deviation during 1000 [ms] before saccade is difference between mean of EEG potential during 1000 [ms] before saccade and maximum amplitude.

$n = \frac{\bar{x}-\mu}{s}$; where $\bar{x}$ is mean of EEG potential during 1000 [ms] before saccade, μ is maximum amplitude, and s is standard deviation during 1000 [ms] before saccade.

Peak time when saccade-related EEG signal is from -6 [ms] to -2[ms] (Ave. = -3.5, STD = 1.1) and n is from 4.4 to 9.3 (Ave. = 7.1, STD = 1.1) in Table 1. From Table 1, features of saccade-related EEG signals were observed before saccade and these features were observed remarkably.

4.2 Results of FICAR

We prepared about 500 reference signals for use in this experiment. As describe above, a reference signal has one peak point because waveform of a reference signal is a impulse wave. The signals differ in the time it took each to peak. The first reference signal has a peak when the stimulus is illuminated, and the time when the second reference signal has a peak is (*the time when the first reference signal has a peak*)+1 [ms]. The time when each reference signal has a peak is (*the time when the previous reference signal has a peak*)+1 [ms]. The final reference signal peaked in 300 [ms] after an eye movement.

Fig.3 shows the experimental results obtained when a subject move his eyes toward a visual and auditory target on the right side. These data are processed using the FICAR against the raw EEG data. The left figures indicate results in visual experiments and the right figures show results in auditory experiments. Top boxes represent the shapes of reference signals and bottom boxes indicate the amplitude

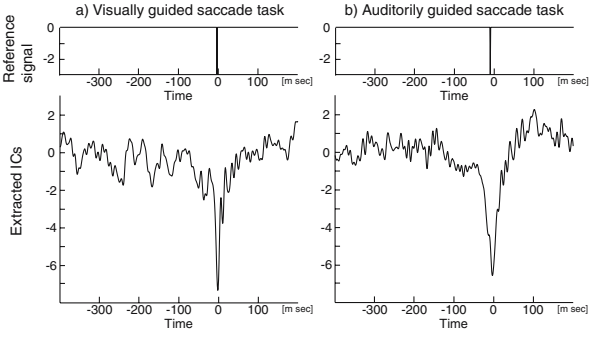

Fig. 3. Extracted signals for FICAR in visual and auditory experiments

of the ICs obtained by using the FICAR. The horizontal axes in these graphs represent the time course, where 0 [ms] indicates the start point of eye movement.

The results show that the amplitude of the signal obtained by the FICAR is sharply changed when a reference signal is set just before eye movements. The shape of the IC that is obtained when the peak of the reference signal occurred prior to an eye movements resembles the shape obtained with the ensemble averaging method (See Fig.2 and 3). The IC which has a peak just before eye movements bears a resemblance to the features of ensemble averaging in respect to the time when the potential incurs a sharp change. In the case of all subject and trials, this component is extracted. Therefore, we conclude that this pre-movement component is related to the saccade-related IC.

4.3 Extraction Rate

Next, we will determine how many of the saccade-related ICs obtained by using the FICAR. Table 2-(a) and 2-(b) represents the rate for extracting saccade-related ICs from the raw EEG data. The extraction rate is defined by ratio:
(*the number of trials in which saccade-related IC are extracted*)
/ (The total number oftrials).

Table 2. Extraction rate for extracting saccade-related ICs in visual and auditory experiments

(a) In visual experiments

Subject	Subject B	Subject C	Subject D	Subject E
Right / Left	Right / Left	Right / Left	Right / Left	Right / Left
60%/88%	60%/64%	52%/64%	80%/80%	88%/80%

(b) In auditory experiments

Subject A	Subject B	Subject C	Subject D	Subject E
Right / Left	Right / Left	Right / Left	Right / Left	Right / Left
92%/84%	68%/72%	76%/68%	60%/80%	52%/88%

The lowest rate was 52%. However, the rate for most of the subjects was over 60% and the highest rate was 92%. The average rate was 72.8%.

In the ensemble averaging results, a sharp change of the EEG signal is recorded each time; however, a subject had to perform the task over 20 trials. On the other hand, in the case of the FICAR, the rate for extracting saccade-related IC is below 100%. However, the saccade-related IC was extract in only two trials, and the ICA method extracted the same feature as the ensemble averaging results in a shorter time than ensemble averaging. Therefore, from the results, we find that the ICA method is more suitable for extracting saccade-related components than the ensemble averaging method. In other words, we have confirmed that ICA is potentially useful for developing BCI.

4.4 Comparison Between Saccade-Related EEG Signal and IC

In order to compare the saccade-related EEG with saccade-related IC, we focus on a time when saccade-related ICs have a maximum amplitude and maximum amplitude. Table 3 shows a time when saccade-related ICs have maximum amplitude and maximum amplitude in results of FICAR. Definition of n was the same as results of ensemble averaging. Value of each cell was calculated by averaging.

Table 3. Peak time and amplitude on sharp change of ICs

	In visual experiments		In auditory experiments	
	Peak time [ms]	$n = \frac{x-\mu}{s}$	Peak time [ms]	$n = \frac{x-\mu}{s}$
	Right/Left	Right/Left	Right/Leftt	Right/Left
A	-12.7 / -12.7	5.6 / 5.2	-13.0 / -16.0	4.8 / 4.6
B	-8.9 / -11.9	3.3 / 5.6	-19.1 / -13.1	3.7 / 3.8
C	-7.8 / -12.5	3.5 / 4.8	–13.4 / -18.6	3.7 / 3.6
D	-12.4 / -16.1	5.9 / 6.1	-7.8 / -13.8	4.5 / 5.0
E	-13.8 / -15.1	6.8 / 6.4	-7.8 / -9.7	4.5 / 5.7
Ave.	-11.5 / -13.7	5.0 / 5.6	-12.2 / -14.2	4.3 / 4.5
STD	3.0 / 1.8	1.5 / 0.6	4.7 / 3.3	0.5 / 0.9

Peak time when saccade-related ICs have maximum amplitude is from -19.1 [ms] to -7.8[ms] (Ave = -12.9, STD = 3.3) and n is from 3.3 to 6.8 (Ave. = 4.9, STD = 1.0) in Table 3. From Table 3, features of saccade-related ICs were observed before saccade and these features were observed remarkably.

Comparing results of saccade-related EEG signal with results of saccade-related ICs, Peak time when saccade-related ICs have maximum amplitude is earlier than peak time when saccade-related EEG signals have maximum amplitude. This is big advantage in the case of developing proposed BCI, the alarm of inattentive driving, and the high-speed targeting system. However amplitude calculated as n in the case of saccade-related ICs is not larger than in the case

of saccade-related EEG signal. Therefore, in the point of S/N ratio, results of ensemble averaging are better than results of FICAR. However, if pre-processing is used before EEG signals are processed by ICA, S/N ratio become better in the case of ICA results.

5 Conclusion

This paper present extraction of saccade-related ICs and compared features of saccade-related EEG signals and saccade-related ICs in the point of a time when saccade-related ICs have a maximum amplitude and maximum amplitude in visual experiments and auditory experiments. Our study shows that EEG signals related to saccade can be extracted by the ICA method. The extraction rate for the saccade-relate IC was 72.8%. This rate is not high enough to apply the ICA method to signal processing for BCIs. Therefore, EEG signals must be used with pre-processing. Comparing results of saccade-related EEG signals with results of saccade-related ICs, peak time when saccade-related ICs have maximum amplitude is earlier than peak time when saccade-related EEG signals have maximum amplitude. This is very important advantage for developing our BCI. However, S/N ratio in being processed by FICAR is not improved comparing S/N ratio in being processed by ensemble averaging. In the future, we will try to obtain a higher extraction rate for extracting the saccade-related ICs and to improve S/N ratio in being processed by FICAR using by advanced ICA algorithms and pre-processing.

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