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Usability of Transient VEPs in BCIs

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1. Introduction

Among non-invasive Brain Computer Interfaces (BCIs), electroencephalogram (EEG) has been the most commonly used for them because EEG is advantageous in terms of its simplicity and ease of use, which meets BCI specifications when considering practical use. In general, EEG signals (EEGs) can be classified into two categories, spontaneous EEGs and stimulus evoked EEGs. Focusing on stimulus evoked EEGs, signals called P300 and Visual Evoked Potentials (VEPs) are often utilized for BCIs. Both types of BCIs extract the intention of users by detecting which target on the PC monitor users are gazing at (Sellers & Donchin, 2006; Sellers, et al., 2006).

While P300 signals are thought to be derived from the thoughts of users, VEPs are simply derived from physical reaction to visual stimulation. In that sense, VEP-based BCIs are thus known as the simplest BCIs.

Most VEP-based BCIs utilize so-called "steady-state VEPs" (SSVEPs) which are generated in reaction to high-speed blinking light (Allison, et al., 2008; Cheng, et al., 2002). Because SSVEPs are characterized by sinusoidal-like waveforms whose frequencies are synchronized with the frequency of blinking light, the gazing target of users can be identified by using frequency analysis of SSVEPs from among several visual targets with different blinking frequencies.

On the other hand, there is another type of VEP called a "transient VEP." Transient VEPs are generated in reaction to low-speed blinking light (i.e., blinking frequency of less than 3.5 Hz), and they can be characterized with a negative peak of around 75 ms and a positive peak of around 100 ms (N75 and P100 in Fig. 1). Unlike SSVEPs, transient VEPs are rarely used for BCIs because it is considered that they need longer detection time than SSVEPs.

However, there are several issues which need to be addressed regarding the use of SSVEP-based BCIs. The first issue is discomfort caused by blinking light. When gazing at high-speed blinking light, some people exhibit symptoms similar to optically stimulated epileptic seizure such as annoyance, headache, or nausea (Graf, et al., 1994; Guerrini & Genton, 2004). Most of the subjects in the authors' study group actually felt discomfort caused by the blinking stimuli. The second issue is that SSVEPs are not detected in all people. One of the reasons for this is considered to be that some people unconsciously refuse to gaze at discomfort targets, and the authors' group included some users in which SSVEPs were not detected. SSVEP-based BCIs cannot be practically used for such kind of users.

Considering these issues, the authors have proposed a transient VEP-based BCI which reduces discomfort caused by gazing at high-speed blinking light (Yoshimura & Itakura, 2009). If long detection time of transient VEPs can be shortened, there is a possibility that the proposed BCI may be put into practical use, especially for users who are easily annoyed with high-speed blinking light. To accomplish this, the proposed BCI employs bipolar derivation to reduce unwanted signals. Moreover, our BCI utilizes non-direct gazed visual stimuli to further reduce discomfort.

In this chapter, a new usability of transient VEPs is introduced, and the possibility that the transient VEP-based BCI can be used as a substitute for SSVEP-based BCIs is shown.

2. Visual Evoked Potentials (VEPs)

VEPs are one of evoked potentials which can be recorded from scalp. Retinal photoreceptor cells located in the retina are discharged by visual stimuli such as light, and discharged electrical signals are transferred to the visual cortex via the visual pathway. The consequential response signals are referred to as VEPs.

VEPs are used in the field of clinical medicine to examine the function of optic nerves and visual cortex. As visual stimuli for the inspection, pattern reversal stimuli which use a switching black-and-white lattice pattern, or flicker stimuli which use blinking LED or flash light, are commonly used. This is because neurons in the visual cortex show high sensitivity to patterns which have a clear shape or contrast, while these neurons show low sensitivity to uniform irradiation to the retina.

VEPs can be categorized into transient VEPs or SSVEPs according to waveform patterns. While transient VEPs occur in reaction to visual stimuli which blink at a frequency of less than 3.5 Hz, SSVEPs occur in reaction to stimuli of higher blinking frequency. Transient VEPs, which are recorded from the occipital area, show triphasic waveforms as shown in Fig. 1, and a positive peak referred to as P100 appears stably at about 100 ms after stimulation.

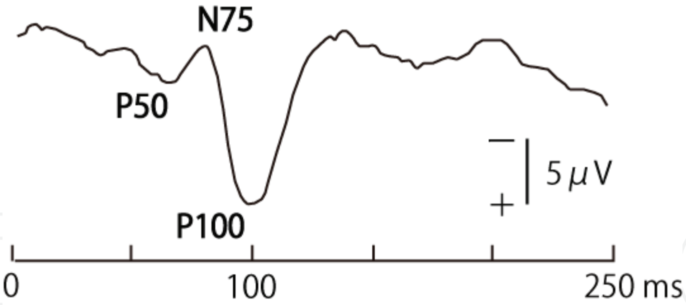


Fig. 1. A typical waveform of transient VEPs. Two positive peaks, P50 and P100, and a negative peak referred to as N75 are shown at about 50, 100, and 75 ms after visual stimulation, respectively (Watanabe, 2004). Waveforms are plotted negative-up in this and all subsequent figures.

On the other hand, sinusoidal-like waveforms are shown in SSVEPs instead of triphasic waveforms as shown in Fig. 2, because signals generated in reaction to single stimulation interfere with other signals which are caused by subsequent stimulation. It is known that frequencies of the waveforms are synchronized with repetition frequency of the stimulation. Therefore, the phenomenon can be referred to as synchronization phenomenon. SSVEP-based BCIs are interfaces based on this synchronization phenomenon.

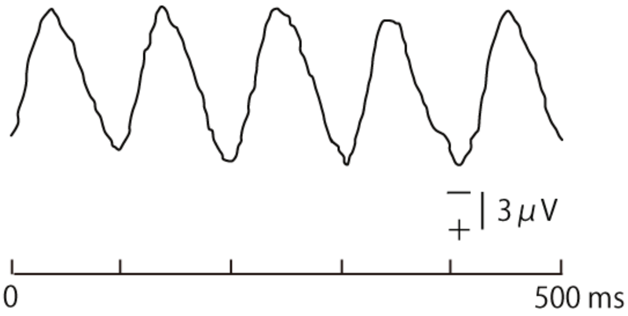


Fig. 2. An example of sinusoidal-like waveforms shown in SSVEPs using 5 Hz blinking visual stimulation (Watanabe, 2004). Frequencies of SSVEPs are synchronized with the frequency of visual stimuli.

3. Availability of transient VEPs

The most important reason transient VEPs are rarely used for VEP-based BCIs may be due to their long detection time. There are two reasons for a long detection time.

One reason is due to the low-blinking frequency of visual stimuli. There is a limit on the shortening blinking interval of visual stimuli because a precedence response and a subsequent response might interfere with each other in the case of a shorter blinking interval, which may result in generating SSVEPs. The other reason is due to the number of epochs which are required for signal averaging. In general, 100-200 epochs are required for signal averaging to detect clear transient VEPs.

Due to these two reasons, it is considered that transient VEPs cannot offer higher performance for BCIs than SSVEPs can in terms of performance on extracting information in a short time. However, considering the issue that there are some users who experience discomfort by looking at high-speed blinking visual stimuli, establishment of a substitute system might be required for such users. If transient VEPs can be recorded in a short time and especially by using non-direct gazed visual stimuli, there is a possibility for providing more comfortable BCIs.

Therefore, as a preliminary experiment, the authors examined the possibility of bipolar derivation and non-direct gazed visual stimuli. While non-direct gazed visual stimuli are expected to reduce discomfort during use, bipolar derivation is expected to reduce unwanted signals such as background noise and signals caused by eye blinking, and thus it will reduce the number of epochs used for signal averaging.

3.1 Short-distance bipolar derivation

There are two methods of recording EEGs, monopolar derivation and bipolar derivation. While monopolar derivation measures the potential between biological reference (i.e. ear lobe) and a measurement point, bipolar derivation measures potential subtraction between two measurement points.

In the field of clinical medicine, bipolar derivation is used to record VEPs, but two distantly-positioned measurement points, one at the midfrontal area and the other at the occipital area, are generally used. This is why about 100 epochs are needed for signal averaging to eliminate background noise.

In this study, therefore, short-distance bipolar derivation using two nearly-positioned occipital measurement points was employed to reduce the number of epochs for signal averaging (see Fig. 4). Although the amplitude of VEPs tends to decrease with the shortening of the distance of measurement points, in-phase signals (i.e. artifacts such as AC noise or eye blinking) cancel each other out, and out-of-phase signals between two measurement points (i.e. VEPs) are expected to be enhanced. Furthermore, it is considered that the number of epochs for signal averaging is surely reduced by locating two electrodes at the right and the left occipital area when considering paradoxical lateralization (Barrett, et al., 1976).

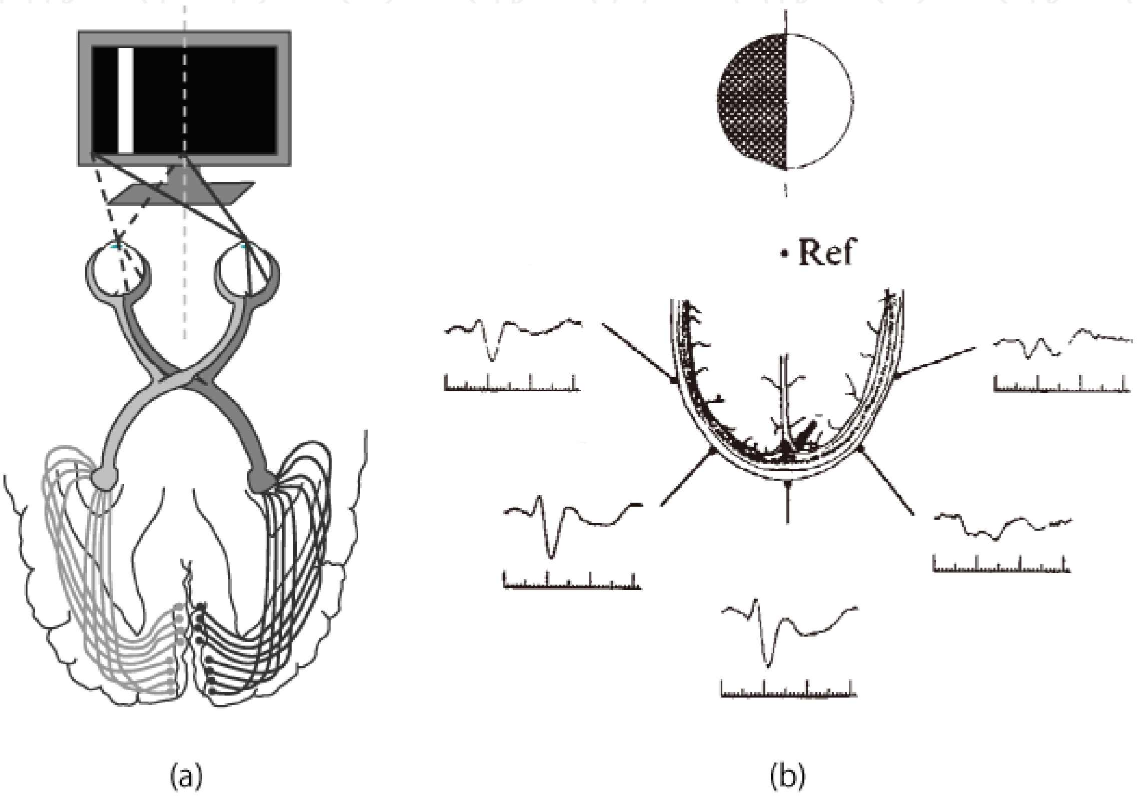


Fig. 3. (a) The pathways from the retina to the visual cortex undergo partial decussation in the chiasma, so that information presented to the left of the visual field passes to the right hemisphere (Watanabe, 2004). (b) Paradoxical lateralization. Stimulation of one half field produces an evoked response which is maximal over the ipsilateral hemisphere, whereas the maximal response is predicted to be recorded over the contralateral hemisphere (Barrett, et al., 1976).

It is known that the VEPs of a half visual field stimulation are recorded maximally from electrodes over the midline and the hemisphere ipsilateral to the field of stimulation, whereas the VEPs on the contralateral side show a comparatively flat or reversed polarity signal. This phenomenon is called paradoxical lateralization (See Fig. 3). Considering this study case, in the case of left visual field stimulation, bipolar records using a right occipital electrode and a left occipital electrode may show difference potential which is subtraction of N100 recorded from the right occipital area from P100 recorded from the left occipital area, resulting in summation of absolute amplitude values of the P100 and the N100. This may alleviate the problem of small amplitudes in the case of bipolar derivation, and characteristic peaks of transient VEPs are expected to be recorded even if the number of epochs for signal averaging is small.

To the best of the authors' knowledge, there have been no studies except that of the authors' which have shown averaged transient VEPs by using a small number of epochs and which investigated evoked response patterns by a half visual field stimulation in the case of bipolar recording using a right occipital electrode and a left occipital electrode (Yoshimura & Itakura, 2008a). Briefly, the experiment is explained in the next subsection. The experiment was performed to verify the possibility of whether the stimulated visual field could be distinguished by VEPs.

3.2 Experiment

(a) Protocol

Signals were amplified with a gain of 94 dB and 0.08-100 Hz bandpass filtered using an electrode input box JB-620J and an amplifier AB-610J (Nihon-Kohden Corporation, Tokyo, Japan). An A/D converter PCI-3153 (Interface Corporation, Hiroshima, Japan) with a 12-bit resolution was set at a sampling frequency of 1 kHz. Three subjects were seated facing a 19-inch PC monitor at a viewing distance of 63 cm under a normal room condition with fluorescent lights and were asked to gaze at a fixation cross point on the monitor.

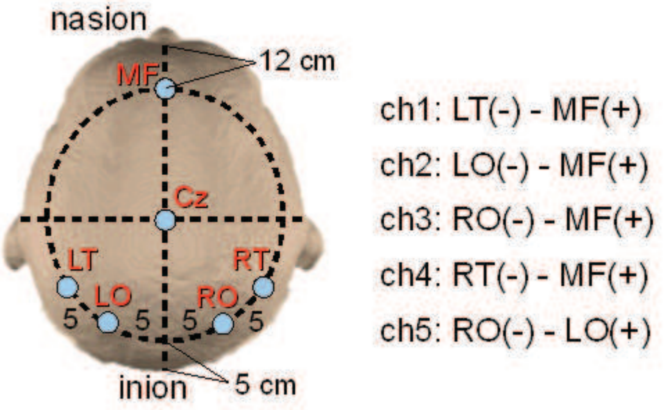


Fig. 4. Electrode positions and channel configuration. Six electrodes were placed over the midfrontal (MF), central (Cz), temporal (LT and RT) and occipital (LO and RO) areas. LO and RO were located 5 cm apart from the position which is located 5 cm above the inion. For channel configuration of bipolar derivation, LT, LO, RO, RT were connected to the minus input, and MF and LO were connected to the plus input. Cz was used as a ground electrode.

Ag/AgCl electrodes were placed over the midfrontal area (MF), the temporal area (LT and RT), the occipital area (LO and RO) and the central area (Cz of the international 10-20 system) as shown in Fig. 4. Cz was used as a ground electrode. Electrode combinations for bipolar derivation are also shown in Fig. 4. A general combination used in clinical medicine was set at ch1-ch4, and a short-distance combination was set at ch5.

As seen in Fig. 5, a white slit was displayed on a black-background PC monitor as pattern-onset stimulation. The most important feature is that subjects were asked not to gaze at the white slit but instead to gaze at a fixation cross point displayed at the center of the monitor. Although responses tended towards higher amplitude in the case of using pattern-reversal stimulation (Torok, et al., 1992), the pattern-onset stimulation was employed to verify whether the response could be recorded under such an adverse condition. The white slit was displayed at several visual angles to investigate the effect on responses.

Epochs were extracted in reference to stimulus onset (spanning +300 ms from a slit display). The mean was subtracted from each epoch, and 15 epochs were used to calculate an averaged signal. The averaged signal was low-pass filtered with a cutoff frequency of 30 Hz.

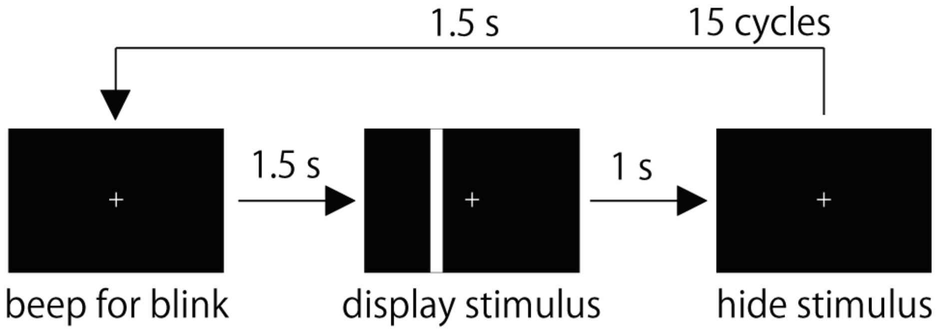


Fig. 5. Experimental sequence. A fixation cross point was placed at the center of the monitor. A non-direct gazed visual stimulus (a white slit with the visual angles of 2.5 degrees horizontally and 24.5 degrees vertically at a view distance of 63 cm) was displayed for 1 s on the left or the right of the fixation cross point with the visual angles of 1.25, 3.75, 6.25 and 13.75 degrees, respectively. The subjects were asked to blink along to a beep sound to avoid extra blinking while the slit was being displayed.

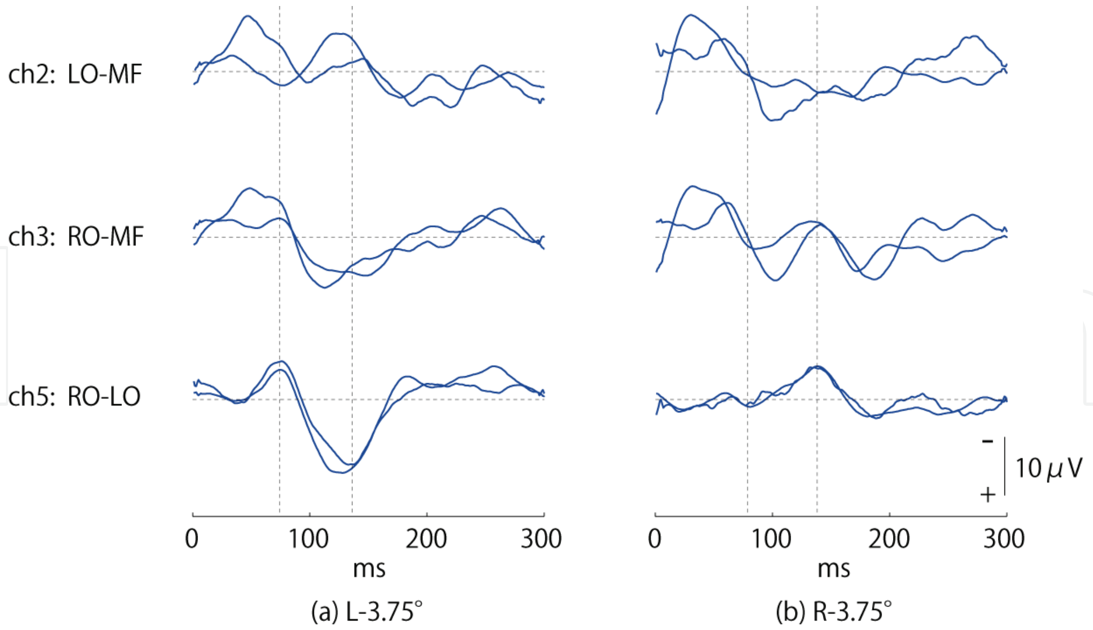
(b) Results

Comparing the averaged signals between different channels, signals of RO-LO (ch5) showed a reproducible pattern in which the differences of the stimulated visual fields can be recognized as shown in Fig. 6.

According to paradoxical lateralization, it is predicted that the maximal signal is recorded from RO-MF (ch3) in the case of the right visual field stimulation and a reversed polarity signal with small amplitude is recorded from LO-MF (ch2). However, signals of LO-MF and RO-MF shown in Fig. 6(b) did not show the predicted signals because of the small number of epochs for signal averaging and non-direct gazed visual stimulation in this experiment. This also happened in the case of the left visual field stimulation (Fig. 6(a)).

In the case of RO-LO (ch5), two characteristic peaks with latencies of around 75 ms and 120 ms were shown even when using non-direct gazed stimulation and a small number of epochs for signal averaging (the vertical dotted lines in Fig. 6). Furthermore, as expected, the polarities of the two peaks were reversed between the right and the left visual field stimulation. For example, the peak with 75 ms latency had a positive peak in the case of the right visual field stimulation (Fig. 6(b)), whereas it had a negative peak in the case of the left visual field stimulation (Fig. 6(a)). This tendency was seen for all visual angles of the slit display position and for all subjects. Therefore, it was considered that RO and LO was the best combination for a BCI. Hereafter the two characteristic peaks are referred to as N/P75 and P/N100 because these peaks seemed to represent N75 and P100 of typical transient VEPs.

To identify which peak, N/P75 or P/N100, was applicable for discriminating gazing direction, grand mean latencies and grand mean amplitudes of these peaks were calculated as shown in Fig. 7. Despite lower amplitudes, N/P75 showed a significantly smaller variation of latencies than P/N100 did. These results seem to indicate that a classification algorithm for gazing direction could be established using data around N/P75.



(a) L-3.75° (b) R-3.75°

Fig. 6. Examples of signals recorded from ch2 (LO-MF), ch3 (RO-MF), and ch5 (RO-LO). Two examples of signals, in the case of the left (a) and the right (b) visual field stimulation with 3.75 degrees of visual angle, were overwritten. Signals of ch5 (RO-LO) showed reproducible peaks with latencies of 75 ms (N/P75) and 120 ms (P/N100). (modification by (Yoshimura & Itakura, 2008a)

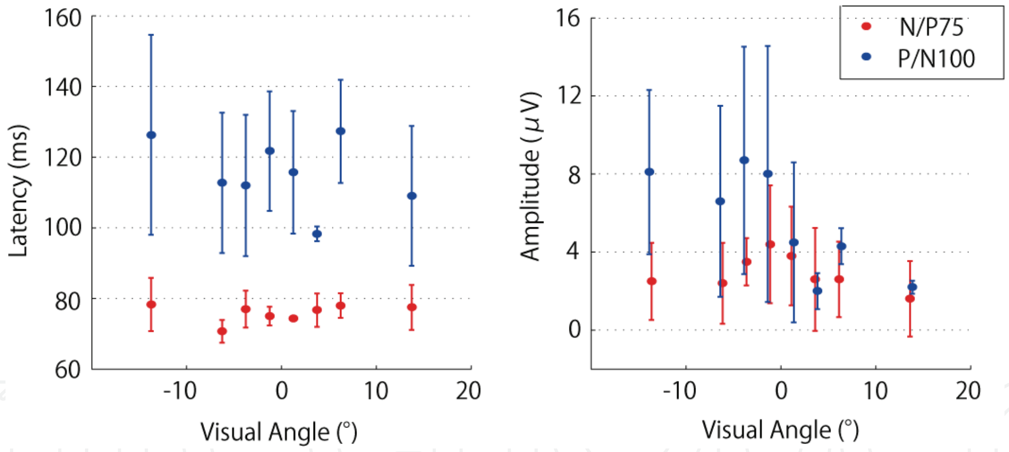


Fig. 7. Grand mean latencies and grand mean amplitudes of N/P75 and P/N100. Latencies of N/P75 showed a significantly smaller variation in comparison to that of P/N100, although amplitudes of N/P75 were relatively small. (Yoshimura & Itakura, 2008a)

In this section, the following results were suggested.

1. VEPs could be detected even when using non-direct gazed visual stimuli.
2. Characteristic peaks of transient VEPs (N/P75 and P/N100) were reproducibly-observed with only 15 epochs of signal averaging when using short-distant bipolar derivation of two electrodes located in the right and the left occipital areas (RO-LO).
3. RO-LO signals showed positive N/P75 and negative P/N100 in the case of the right visual field stimulation, whereas they showed negative N/P75 and positive P/N100 in the case of the left visual field stimulation.

4. Comparing N/P75 and P/N100 in terms of interfaces development, it was found that N/P75 would be applicable to a classification algorithm for gazing direction because N/P75 had smaller variation of latencies.

These results suggested that transient VEPs recorded by conditions shown in this section can be used for a BCI. In the next section, therefore, two kinds of BCIs are proposed, and their patterns of responses are investigated.

4. Comfortable BCIs using non-direct visual stimuli

4.1 Proposed BCIs

Two types of BCIs (Type I and Type II) were proposed as shown in Fig. 8. Both of them have characteristic specifications in which low-speed reversal stimulation and non-direct gazed visual stimuli were used.

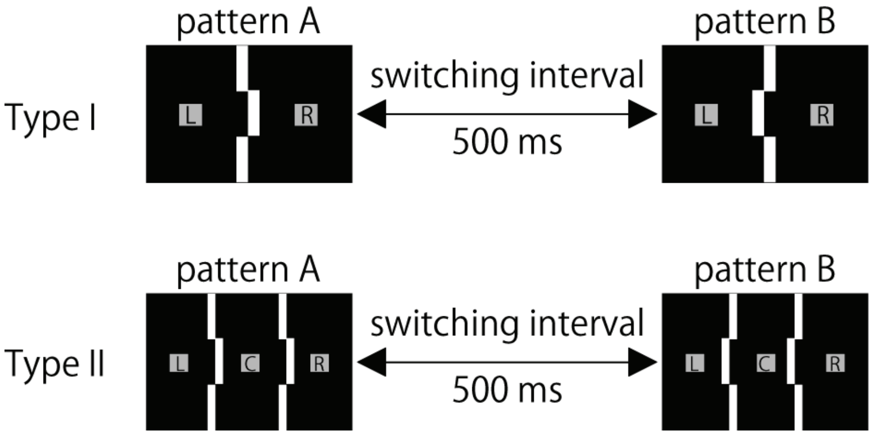


Fig. 8. Schematic diagrams of the proposed BCIs. Type I (above): A white lattice pattern, pattern A and pattern B, is displayed alternately on a black background of a 19-inch PC monitor as visual stimuli. The pattern has the visual angles of 2.5 degrees horizontally and 24.5 degrees vertically at a viewing distance of 63 cm. Square-shaped visual targets with the visual angles of 1.5 degrees (L or R) are displayed at 9 degrees to the left or right side of the pattern (Yoshimura & Itakura, 2008b). Type II (below): A pair of two white lattice patterns, pattern A and pattern B, is displayed on the PC monitor as visual stimuli. The pattern has the visual angles of 2 degrees horizontally and 24.5 degrees vertically at a viewing distance of 63 cm. Square-shaped visual targets with the visual angles of 1 degrees (L, C or R) are displayed at the center of the screen (C) and at 7 degrees to the left (L) or right (R) side of the pattern (Yoshimura & Itakura, 2009).

(a) Type I

A white lattice pattern, pattern A or pattern B, is displayed on a black background of a 19-inch PC monitor as a visual stimulus. The pattern switches between pattern A and pattern B at switching intervals of 500 ms. Subjects were asked to gaze at a gray visual target indicated by the black letter L or R located at the left or the right side of the switching pattern. This specification was determined with the aim of classifying subjects' gazing direction, right-gazing or left-gazing, according to the difference of N/P75 peaks mentioned in section 3. For example, in the case of subjects gazing at the right target, characteristic peaks of left side stimulation are expected because the switching pattern is displayed at the left visual field of the subjects.

(b) Type II

While it is assumed that subjects always gaze at the right or the left side of the monitor in Type I, Type II was designed based on the assumption of real-time classification which works with movement of gazing direction. Therefore, a specification requiring subjects to change their gazing direction from the center (center-gazing) to the left (left-gazing) or the right (right-gazing) was proposed.

A pair of two white lattice patterns, pattern A or pattern B, is displayed alternately on a black background of the PC monitor as visual stimuli. The switching intervals were also set at 500 ms. The biggest difference between Type I is that Type II has two switching patterns to divide the screen into three sections. This specification maintains the comfortable feature because subjects do not have to gaze at the switching pattern directly even during center-gazing. In addition, the widths of the lattice patterns and the visual targets were smaller than those of Type I considering the smaller areas of split screens.

When subjects gaze at the center target in Type II, visual stimulation is given from both visual fields, the right visual field and the left visual field. If VEPs in response to the stimulation in Type II follow the theory of paradoxical lateralization, signals during center-gazing are predicted to become relatively flat by canceling out responses from the dual stimuli. On the other hand, when subjects move their gazing direction to the right or the left, the responses are expected to become larger because the dual stimulation is provided from the same direction with different visual angles.

(c) Common features of Type I and II

The sizes of the lattice patterns are not usual for VEP recordings in the field of clinical medicine (Torok, et al., 1992). Although it was reported that amplitudes of responses differed according to differences of stimuli patterns (Suttle & Harding, 1999; Torok, et al., 1992), the tendency might be different between subjects. Especially in this research, because the number of epochs used for signal averaging is quite smaller than that of other research, it is considered that the influences of individual difference might be greater than that of patterns differences. Therefore, the sizes of the patterns were determined based on feedback from subjects in terms of reducing discomfort.

Furthermore, the positions of the visual targets, visual angles of 9 degrees, were also determined based on feedback from subjects despite responses with possible larger amplitudes and smaller variation of latencies when setting the visual targets close to the center of the screen (as seen in Fig. 7). Keeping the targets away from the center of the screen may lead to another advantage in terms of subjects not being bothered by the switching stimuli.

Several improvements were made to the experiment as discussed in section 3. First, the type of stimulation was changed from pattern-onset to pattern-reversal to minimize the stimulation interval as much as possible. Second, a beep sound for the eye blink was discontinued to make the interface suitable for practical use, and the number of pattern switchings in one trial was increased from 15 times to 20 times to sufficiently cancel artifacts of eye blinking by signal averaging.

The advantage of the proposed interfaces is that discomfort of blinking stimuli could be reduced by low-frequency of pattern switching and non-direct gazed visual stimuli. The possibility of the BCIs was validated by the following experiment (Yoshimura & Itakura, 2008b; Yoshimura & Itakura, 2009).

4.2 VEP patterns of the proposed BCIs

(a) Experimental protocol

Six healthy subjects (3 male and 3 female), between 33 and 39 years of age, participated in the experiment. All subjects had normal or corrected-to-normal vision and were right-handed. Electrodes were placed as shown in Fig. 9. Besides RO and LO shown in Fig. 4, PLO, PRO, CLO and CRO were also investigated to identify the best position for each subject.

The system configuration was the same as described in section 3.2(a). Each subject performed 20 trials consisting of 10 each for the right and the left gazing directions in random order. Epochs were extracted in reference to stimulus onset (spanning +300 ms from a pattern switching). The mean was subtracted from each epoch, and 20 epochs were used to calculate an averaged signal. The averaged signal was low-pass filtered with a cutoff frequency of 30 Hz. Detailed protocol of one trial for Type I and Type II is described below.

1. Type I:
   Subjects were asked to gaze at either of the visual targets (L or R) on the monitor and to maintain the gazing direction for about 10 s until the lattice pattern switched 20 times.
2. Type II:
   A trial began after the subjects started gazing at the visual target with the letter C in Fig. 8 (i.e., center-gazing). When the letter C changed to another letter, L (left) or R (right), after 10 occurrences of pattern switching (about 5 s), the subjects changed their gazing direction from the center to the left (i.e., left-gazing) or to the right (i.e., right-gazing) according to the letter L or R. Then their gazing direction was maintained for another 20 occurrences of pattern switching (about 10 s). Signal averaging was performed by using 20 of the most recent epochs, except for the first 19 epochs which used all epochs recorded from the beginning of a trial.

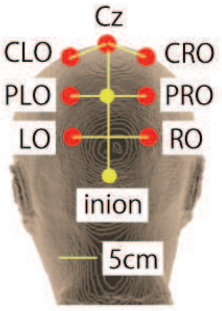


Fig. 9. Electrode positions. Three pairs of electrodes over the occipital (LO and RO), parietal (PLO and PRO), and central (CLO and CRO) regions were used to construct three channels of bipolar derivation. LO, PLO, and CLO were connected to the plus input, and RO, PRO, and CRO were connected to the minus input. A ground electrode was applied over Cz.

(b) Results

Fig. 10 shows examples of VEPs in the case of Type I. While N/P75 was shown to be similar to that in Fig. 6 in section 3, P/N100 was not clearly shown to be similar. This may have been because the display interval of stimuli was shortened from 3 sec to 500 ms.

Next, waveform examples in the case of Type II are shown in Fig. 11. In the case of left-gazing (a red line), N/P75 and P/N100 were shown, but N/P75 was not shown in the case of right-gazing (a blue line). Moreover, the waveform of center-gazing did not show a flat peak contrary to expectation. These results seemed to indicate that transient VEPs were detected in Type II, but that the waveforms became complicated due to the dual stimuli from different visual angles. Especially in the case of center-gazing, the dual stimuli were provided from different directions, left and right, and thus responses to these stimulations might not have become flat but complicated by interfering with each other.

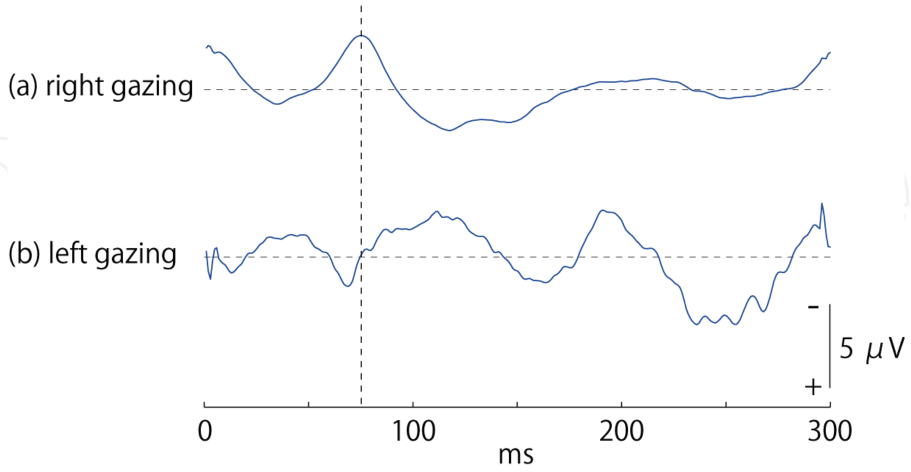


Fig. 10. Examples of transient VEPs in Type I during right-gazing (a) and left-gazing (b). Characteristic peaks appeared at around 75 ms (a vertical dotted line). A negative peak was shown in the case of right-gazing, whereas a positive peak was shown in the case of left-gazing.

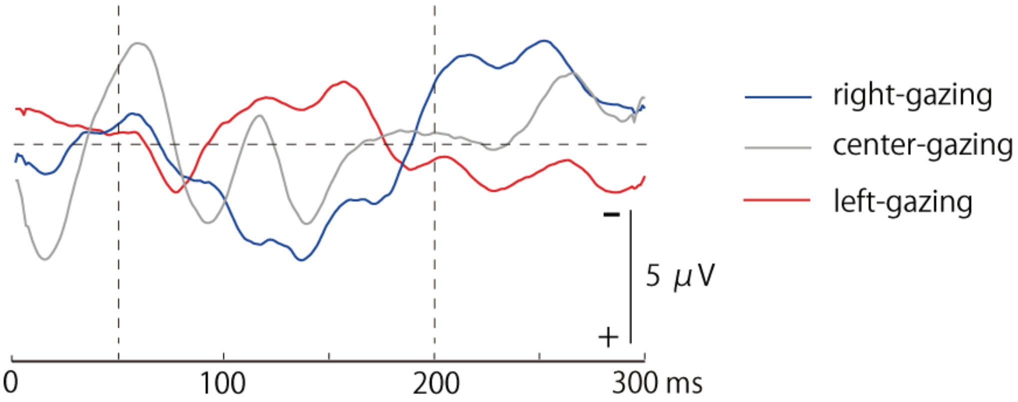


Fig. 11. Examples of waveforms for three gazing directions in Type II. Although N/P75 and P/N100 were not clearly shown, a waveform between 50 to 200 ms (between two vertical dotted lines) shifted to negative voltages when the subject changed the gazing direction from the center to the left, while the waveforms shifted to positive voltages when changing the gazing direction was changed from the center to the right.

4.4 Results: classification of gazing direction in Type II

In the case of Type I, the gazing direction of the left or the right was found to be classified with a 90% mean accuracy by using data around 75 ms from the pattern switching (Yoshimura & Itakura, 2008b). In order to aim for more practical BCIs, classification of gazing directions in Type II was also investigated, and an 84.2% mean accuracy was obtained by using shifts of the waveforms between 50 to 200 ms (Yoshimura & Itakura, 2009). Briefly, the classification method is explained below.

When signals of left- or right-gazing were compared with the center-gazing signal shown in Fig. 11, it was found that signals between 50 to 200 ms shifted to negative voltages during left-

gazing and to positive voltages during right-gazing. Focusing on the shift, the areas surrounded by signals between 50 to 200 ms and x-axis were calculated using quadrature by parts, and the areas were compared between the gazing directions as shown in Fig. 12. It was suggested that changing the direction of gazing could be classified by comparing the area between center-gazing and right-gazing or left-gazing. There are minus values because the total areas were calculated by subtracting areas of plus voltage from areas of minus voltage.
In addition to the method above, we also employed another method in the same manner but using the waveforms between 50 to 100 ms because some subjects showed larger shifts in the range of the waveforms. A calibration step was used to select an appropriate method and an appropriate pair of electrodes for each subject, and real-time classification accuracies of gazing direction were obtained as shown in Fig. 13. The accuracies were improved when

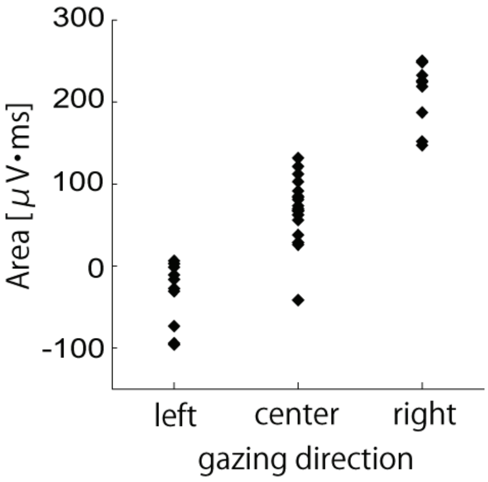


Fig. 12. Comparison of areas between different gazing directions (Yoshimura & Itakura, 2009). Areas of left-gazing tend to be smaller than those of center-gazing, whereas areas of right-gazing tend to be larger than those of center-gazing.

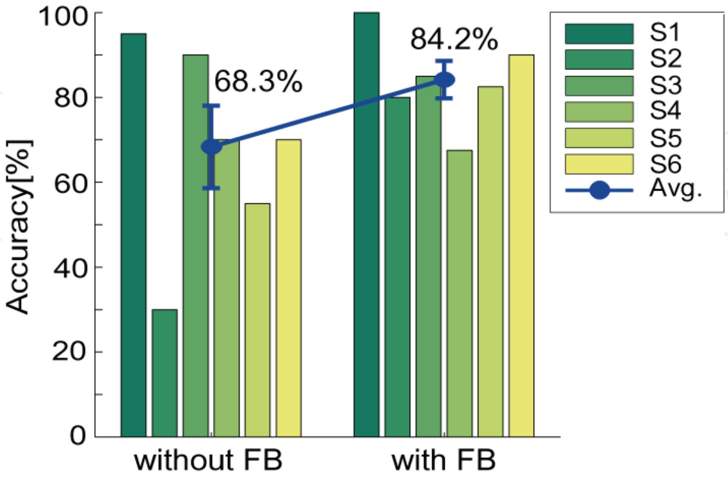


Fig. 13. Real-time classification accuracies of 2 gazing directions, left- and right- gazing (Yoshimura & Itakura, 2009). Accuracies became higher when subjects were given tentative classification feedback of gazing direction in the middle of each session (indicated as “with FB” in the figure).

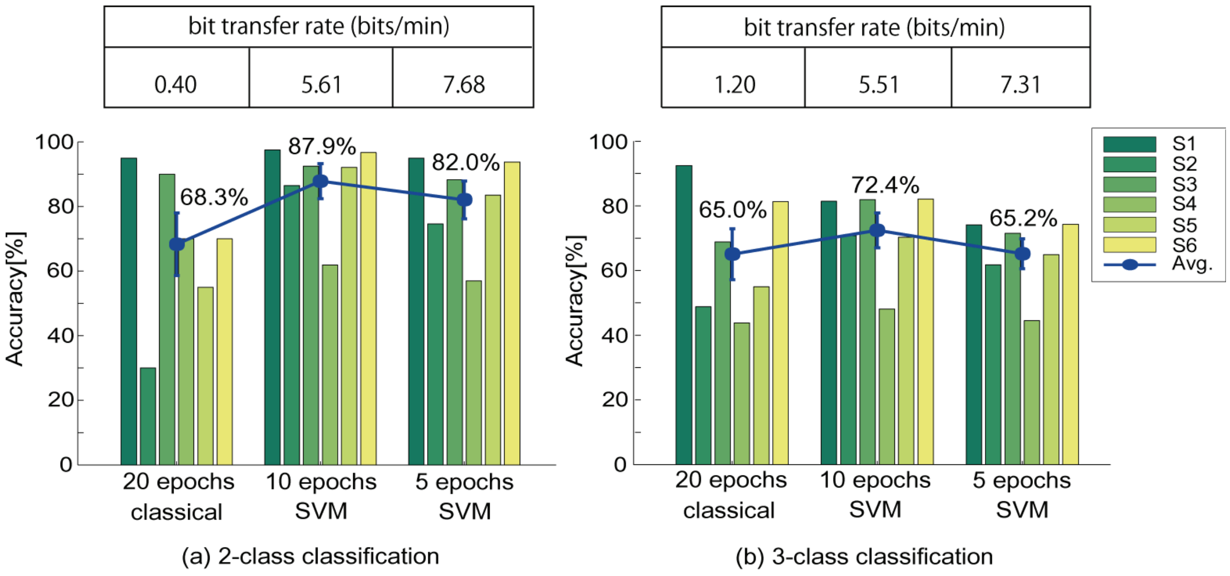
using the midstream feedback (FB) which gave a classification result to subjects in the middle of a trial as feedback. The FB might help subjects to control the final classification results to be consistent with actual gazing directions.

These results suggest that a more comfortable BCI could be established based on transient VEPs using non-direct gazed visual stimuli. In the next section, the possibility of a machine learning approach was investigated in order to obtain higher classification accuracies.

5. Machine learning approach

5.1 Comparison of classification accuracies

To discern future potential of the proposed BCI, classification accuracies were compared between the classical method introduced in section 4 and a method called support vector machine (SVM). SVM is one of the most popular machine learning methods, and it has often been used for BCIs. A two-class or a three-class nonlinear SVM was conducted using LIBSVM, an SVM software package (Chang & Lin, 2001). A radial basis function was used for the SVM kernel. Data obtained in real-time classification without FB (Fig. 13) were used to compare accuracy rates with the classical method in section 4. Fig. 14(a) shows accuracy rates of a 2-class classification (two moving directions of gazing, from the center to the right or to the left), and Fig. 14(b) shows accuracy rates of 3-class classification (center-gazing, right-gazing, or left-gazing). Although the classical method required 20 epochs (10 seconds gazing after moving the gazing direction) for signal averaging to obtain the mean accuracy of 68.3 %, SVM obtained higher accuracy rates even using only 10 epochs (5-second gazing data) or 5 epochs (2.5-second gazing data).



(a) 2-class classification

(b) 3-class classification

Fig. 14. Comparison of classification accuracies between classical approach and SVM (offline classification). (a) Comparison in the case of 2-class classification, left- and right- gazing. (b) Comparison in the case of 3-class classification, left-, center-, and right-gazing.

Furthermore, SVM showed a higher mean accuracy in the case of the 3-class classification using 10 epochs (72.4 %) than the classical method in the case of the 2-class classification using 20 epochs (68.3 %) even though the 3-class classification showed overall lower accuracies than the 2-class classification. Therefore, it was suggested that performance of the BCI could be enhanced more using the machine learning method.

5.2 Comparison of bit transfer rate

The concept of bit transfer rate (BTR) is commonly used to validate BCI performance. BTR indicates the amount of information input per unit time and can be calculated using the following formula (1) (McFarland, et al., 2003),

$$\text{BTR (bits/min)} = (\log_2 N + P \log_2 P + (1-P)\log_2[(1-P)/(N-1)]) * 60/T \tag{1}$$

where N is the number of possible targets, P is the accuracy rate, and T is the required time for 1 command in a second.

BTRs of the proposed BCI were calculated as shown in Fig. 14. The highest BTR was found to be obtained in the case of SVM 2-class classification using 5 epochs, and SVM 3-class classification using 5 epochs also showed a relatively high BTR despite its low accuracy. These BTRs are not higher than BTRs shown in other research (Cheng, et al., 2002), but still they can be said to be as practicable BTRs as a BCI, therefore these results suggested the possibility of the proposed BCI using transient VEPs.

6. Conclusion and future research

This research proposed a new approach showing that transient VEPs could be used not only in the field of clinical medicine but also for BCIs, and it showed the possibility of the new approach through several experiments. Transient VEP-based BCIs may have an advantage when compared to SSVEP-based BCIs because low-speed blinking frequencies less than 3.5 Hz are used for detecting transient VEPs, which could suppress specific discomfort symptoms often seen in people who gaze at high-speed blinking visual stimuli. Furthermore, this research achieved a more comfortable feature by incorporating non-direct gazed visual stimuli into the proposed BCI.

The proposed BCI showed practicable performance as a BCI (more than 7 bits/min of BTR), and also could incorporate a worthwhile feature which might classify a situation in which subjects do not gaze at either of two visual targets but instead gaze at the center of the screen.

However, the number of visual targets (commands) is still much less than that of other published BCIs, so there are several issues which need to be addressed to make the proposed BCI more practicable. As a future work, it will be necessary to increase the number of visual targets by incorporating features of classifying not only using several horizontal positions but also using several vertical positions of visual targets.

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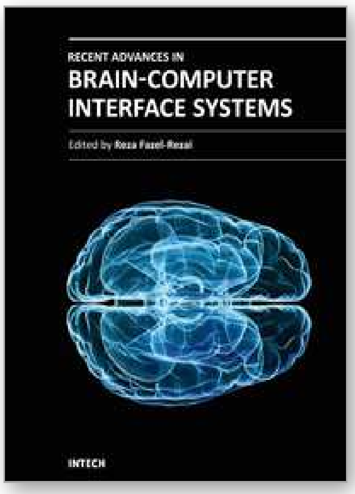

Recent Advances in Brain-Computer Interface Systems
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Brain Computer Interface (BCI) technology provides a direct electronic interface and can convey messages and commands directly from the human brain to a computer. BCI technology involves monitoring conscious brain electrical activity via electroencephalogram (EEG) signals and detecting characteristics of EEG patterns via digital signal processing algorithms that the user generates to communicate. It has the potential to enable the physically disabled to perform many activities, thus improving their quality of life and productivity, allowing them more independence and reducing social costs. The challenge with BCI, however, is to extract the relevant patterns from the EEG signals produced by the brain each second. Recently, there has been a great progress in the development of novel paradigms for EEG signal recording, advanced methods for processing them, new applications for BCI systems and complete software and hardware packages used for BCI applications. In this book a few recent advances in these areas are discussed.

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