Event Related Hemodynamics and Potentials evoked by Visual Attention Task*

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This paper discusses "visual attention" related hemodynamics and potentials during performance of modified paced visual serial addition test (mPVSAT). In researches for human cognitive function, "attention" is regarded as the basis of all mental abilities or human actions. The mPVSAT task, as our revised version of standardized test concerning attention, also needs higher-order attention to solve the test. Then, in order to make clear the mechanism of attentional function, brain activity is evaluated by event related hemodynamics (ERH) and event related potentials (ERP) in our study. From the results, some typical areas with high processing speed or large volume of blood flow are shown. Judgement and recognition process tend to be slow while complicated stimulus in visual attention task.

1. Introduction

One of the important things in human life is cognitive activity by normal brain function. Among them, attention is known as one of the most fundamental functions for human being. The process of attention associates with function included in working memory, so that brain keeps necessary information temporarily in some fixed areas and handles the problem [1]. The area in brain concerning attention is called Broadmann's Area 9 and 46 [2]. On the mechanism of attention, Sohlberg and Mateer proposed attention process model which classified its hierarchy into five levels: focused, sustained, selective, alternating and divided attention.

All brain activities including attention are normally evaluated by neural (electric) activity. Simultaneously, oxygen and glucose are used in active area where nerve activity is evoked. Those components are used to produce energy in these areas. The capillary reaction that occurs at that moment is called neurovascular coupling (NVC) [3]. According to NVC, we evaluate brain blood flow in the form of oxygenated hemoglobin concentration (Oxy-Hb) for our research, in addition to electric potential on brain. Oxy-Hb can be measured by near-infrared spectroscopy (NIRS) and is also known for its usefulness for mental diseases such as depression [4].

Changes of electrical potentials in brain are caused by various mental activities, external or internal stimulus. Generally, stimulation to brain evokes the primary signal (neural activity), then evokes the secondary signal (e.g. blood flow). The interval between these two signals is said to be approximately 0.5s. According to the fact, the mechanism in brain is partly recognized that neural activity and brain blood flow are closely related each other [5].

All properties derived by hemoglobin concentration are called event related hemodynamics (ERH), whereas those on electric potentials are called event related potentials (ERP). The latter is often used for evaluation of brain activity because it is regarded as a cognitive and judgement process of endogenous sensory information. By ERP, endogenous component is measured by subtraction method that offsets exogenous component [6].

The authors have studied on attentional function using instruments these years. In previous researches, NIRS and EEG are used and time series of Oxy-Hb were evaluated. They first focused on auditory attention and made clear that volume in left dorsolateral prefrontal cortex (DLPFC) at frontal lobe increased, by performing paced auditory serial addition test (PASAT) which relates to auditory attention [7]. Then they focused on visual attention in order to suggest the difference between visual and auditory attention. Referring to these previous works, our research in this paper uses modified paced visual serial addition test (mPVSAT) as an experiment and consider brain activity by observation of multiple measurement.
2. Experimental Methods

The conditions of mPVSAT are described in this section. The data were obtained from 20 healthy subjects (15 males and 5 females, age range 20 to 22 years). The experiments were performed in a shield room in order to block additive noises: external sounds and light stimuli. All subjects were well informed and consented to all conditions of the experiment prior to start it. This study has been approved by the Ethics Committee for Human Research at Kokushikan University.

2.1 Modified PVSAT

Attention disorder is one of the serious troubles arising in various higher-order cognitive functions. The PVSAT is one of the tests relating to visual attention. It is the revised version of PASAT, developed by Gronwall, and used to evaluate or judge attention disorders in neuropsychology. PASAT is standardized and included in Clinical Assessment for Attention (CAT) that is issued in 2006 by the Japan Society for Higher Brain Dysfunction. PVSAT, adopted in the experimental task of this paper, is originally a visualized version of PASAT by Fos LA et.al.[8]. Under these conditions, the authors used PASAT or PVSAT in the researches. However, there were some problems on measuring brain activities while performing these tests. The reasons were, that these tasks needed utterance to answer the question, so that the data often included artifacts or noises. Another test with few additive noises is expected in evaluating brain function correctly. Therefore in this paper, we propose modified PVSAT, “mPVSAT” in short, that let a subject judge true or false of answer only in mind without uttering. In mPVSAT, true answers indicate control task whose appearance rate is 80%. False answers, on the other hand, indicate rare task whose appearance rate is 20%. In addition, the subjects are ordered to count a number of false answers to focus on the task. Herewith, we expect that mPVSAT is able to extract complex endogenous component deriving from focused attention, working memory and selective attention by instantaneous judgement of errors.

In this paper, mPVSAT of the display time 0.5s and interval to the next task 1s is adopted as experiment. The number of question and answer are 100, then total time for task is 150s (Fig.1).

2.2 Experimental Instruments

In this experiment, mPVSAT is evaluated by hemodynamics and neurodynamics using NIRS and EEG. The type of NIRS used for this experiments is wearable optical topography system (WOT-100, Fig. 2(a)) manufactured by HITACHI HIGH TECHNOLOGIES, Japan, (b) MUSE brain system manufactured by DIGITAL MEDIC, Japan, (c) The scene of fitting instruments on the head,(d) M-biolog system with brain wave sensor DL-160B, manufactured by S&ME Company, Japan.

In measuring EEG, two types of sensors are used in this paper. The one is MUSE brain system, man-
mufactured by DIGITAL MEDIC (Fig. 2(b)), whose sampling rate is 1 kHz. This is used for simultaneous measurement with NIRS. Subjects put the sensor on their Cz position referring from the international 10-20 positions (Fig. 2(c,d)). ERH is derived in the same procedure as ERP, by taking ensemble average on their Cz position referring from the international 10-20 system position. MUSE brain system was attached on Fpz, F3, F4, C3, C4, P3, P4, Oz positions.

The other is M-biolog system with brain wave sensor DL-160B, manufactured by S&ME Company. This is used for measurement without NIRS but is possible to measure by eight channels (dish electrodes). Using the International 10-20 system, we make measurements (Fig. 3). The data are recorded at a sampling frequency of 1 kHz.

3. Analytical Techniques

Three instruments are used for measuring hemoglobin concentration or electric potentials during mPVSAT in this paper. Hemoglobin concentrations are measured at 16 channels with sampling interval 5Hz, where EEGs are measured at 9 channels (1 point by MUSE system and 8 points by m-biolog system) with 1kHz. In order to analyze data which have inherent properties, the authors apply some techniques in addition to the normal statistics. The first is estimation by auto-regressive model. The second is hierarchical components analysis (PCA) and multivariable autoregressive (MAR) modeling. The reason of using the techniques is that there are comparatively many channels in both instruments, the method including data reduction step is expected.

3.1 Autoregressive Modeling

Estimation by autoregressive (AR) model is one of the standard analytical techniques to present stochastic process. The model is given by (1) for single dimension case.

$$x(n) = e(n) + \sum_{i=1}^{p} a_i e(n-i)$$  \hspace{1cm} (1)

where \( \{x(n)\} \) is observed measurements, \( \{e(n)\} \) is Gaussian white noise. \( p \) is the model order defined by FPE in the paper. \( \{a_i : i = 1, \ldots , p\} \) is estimated parameters of the model. The technique using Yule-Walker equation (2) is adopted here. \( R_k \) is correlation function.

$$
\begin{bmatrix}
R_0 & R_1 & \ldots & R_{p-1} \\
R_1 & R_0 & \ldots & R_{p-2} \\
\vdots & \vdots & \ddots & \vdots \\
R_{p-1} & R_{p-2} & \ldots & R_0
\end{bmatrix}
\begin{bmatrix}
a_1 \\
a_2 \\
\vdots \\
a_p
\end{bmatrix}
= -
\begin{bmatrix}
R_1 \\
R_2 \\
\vdots \\
R_p
\end{bmatrix}
$$  \hspace{1cm} (2)

3.2 Hierarchical Decomposition Method

Hierarchical decomposition is one of the multivariable AR modeling techniques including principal components analysis (PCA). In the method, a data vector is constructed by measurements \( \{x_i(n)\} \), where \( i = 1, \ldots , M \) is the order of the channel. \( N \) is the data length.

At the first step, data vector \( X \) is decomposed by PCA as (3), where \( C \) is spatially weighted matrix, \( W \) is diagonal matrix of eigenvalues. The matrix \( T \) is principal component which is used by following steps. PCA is used to reduce the number of components, as is seen by (3) that matrix (row size \( M \)) to smaller matrix (row size \( F \)). The number of channels \( F \) is selected by certain level of contribution rate, which we apply the threshold of \( M^{-1} \) as referred from [9] in this paper.

$$X = CTWT$$  \hspace{1cm} (3)

The next step, resultant matrix \( T \) is modelled by autoregressive form. MAR model (4) composed of \( T_{p,n} \) is determined by minimizing the sum of squared residual values (5).

$$T_{p,n} = R_{p,n} + \mu_p^{-1} \sum_{q=1}^{P} \sum_{l=1}^{L} A_{q,p,l}T_{q,n-l}$$  \hspace{1cm} (4)

$$R_{MLAR} = \sum_{p=1}^{P} \sum_{n=1}^{N} R^2_{p,n}$$  \hspace{1cm} (5)

\( \mu_p \) denotes a mean value, \( R_{p,n} \) denotes a residual value and \( A \) denotes three-dimensional matrix of estimated model parameters given by autoregressive modeling method 3.1.

The following steps are needed because the model is not unique from the above steps. The 3rd step is to seek transformation matrix \( K \) which orthonormalizes the innovations. New temporal components and new estimates are given by (6),(7).

$$T' = KT$$  \hspace{1cm} (6)
However, it does not fully resolve the non-uniqueness problem. The final step is to search for a rotation whose transformed temporal components consistent with the hierarchical structure. The name HD comes from this structure. If we denote transformation matrix as $Q$, $Q$ is obtained iteratively via a procedure similar to Jacobi matrix diagonalization.

Finally, HD components are chosen by (8) and (9), where $T_{HD}$ represents HD components decided from the data vector $X$

$$T_{HD} = QT'$$

$$A_{HD}^T = QA_{HD}^TQ^{-1}$$

If succeeded, estimates of MAR model $A_{HD}$ are of upper triangular form. The upper triangular parameters are weights for feed-forward interactions. The lower triangular elements characterize feedback interactions and the diagonals are the self-driving weights describing the contribution to itself.

4. Results & Discussions

4.1 Properties of ERH and ERP

First, the mPVSAT score is shown by Fig. 4. False answer appeared at the rate of 20% in mPVSAT. In this experiment, average rate of subject’s answer is 17.3%. Most subjects answered less than the number of correct answers. The result suggests that subjects discriminate between rare stimulus and frequent stimulus in mPVSAT.

Original measurement results of subject-A are shown by Fig. 5(a). Then, we calculate ERP and ERH by taking ensemble average of each event signal. The results are from Fig. 5 to Fig. 7, for the frame length of 1.5s (display time 0.5s plus interval 1.0s). By comparing the transition of ERH and ERP, the response of rare stimulus tends to be slower than frequent stimulus. On ERP, if we calculate the difference between each stimulus, we have Fig. 6. The latency of elicited positive deflection in subject-A appears at early stage after presented stimulus.

Then, time average of ERH for each channel of subject-A is shown in Fig. 7, where the upper figure describes the average of Oxy-Hb for rare stimulus. The middle describes the average for frequent stimulus and the lower describes for rare minus frequent. Time average of ERH means the change of hemodynamics during mPVSAT task. From Fig. 7, ERH which subtracted frequent from rare stimulus show a positive value in almost all channels. Channels around on both sides of frontal lobe show comparatively bigger Oxy-Hb in rare stimulus. These results suggest that Oxy-Hb on both sides of prefrontal cortex increases at rare stimulation. Other subjects also show similar tendency.

4.2 Evaluation by AR Model

In this subsection, EEG is modelled by AR model. The data length for each epoch(frame) is 1500 (=1.5s). The epoch shifts every 100 (=0.1s) from the beginning to the end of measured EEG. In each epoch, the order of AR model is selected by FPE. The results for subjects (A, H, and I) are shown in Fig. 8 where x-axis shows transition of epochs (or frames). From Fig. 8, the difference between rare and frequent stimulus are not clear in the selected order, but some models have
small order which is less than 10. The difference in order means difference in property of the model in each epoch.

As for Oxy-Hb, HD method is applied. Among 14 observation channels, the number of selected components is mostly 1 or 2, which are very simple. This indicates the simple structure of visual attention in Oxy-Hb model. Hierarchically decomposed components are shown in Fig. 9. The upper graph shows the results of subject-A, with 2 selected components. The lower graph shows the results of subject-H whose component is only 1. We cannot see unified trend in these graphs, but HD component tends to be small in case of only 1 component, and each component shows a contrasting trend of increase and decrease in case of 2 components.

4.3 Additional measurement of EEG

In addition to previous results, this section shows ERP results measured by eight channels. As aforementioned in Fig. 3, the measurement positions are Fpz, F3, F4, C3, C4, P3, P4 and Oz in international 10-20 system positions. First, the ERPs which subtracted frequent from rare stimulus of each channel are described in Fig. 10. The HD components of ERP are shown in Fig. 11. Positive deflection around 500ms assumes to be elicited by notification to rare stimulus.

Then we observe the latency of P300 and N200 for evaluation of attentional function, and calculate the difference between them, we have Fig. 12. Here, the latency of N200 is the minimum value 180-360ms. And, the latency of P300 is the maximum value 300-600ms. The interval between N200 and P300 tends to expand for rare stimulus presentation.
5. Conclusions

In this paper, mPVSAT was used for attentional control task. It was the modified version of PVSAT concerning visual stimulus. Comparing with PASAT or PVSAT, the task performance process was more complicated and difficult. From AR model approach, the result indicates the simple structure of visual attention in Oxy-Hb model. Also, both sides of frontal lobe have comparatively bigger Oxy-Hb in rare stimulus. Finally the interval between N200 and P300 suggested that judgement and recognition in case of rare stimulus were delayed from frequent stimulus.

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