The Single-trial Analysis of P300 and the Difference Threshold of Modulated Vibration

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Keywords: tactile sensor, modulated vibration, difference-threshold, P300, single-trial analysis

This study focuses on the tactile display that uses the modulated vibration. Modulated vibration includes two types of single-frequency vibration: one with a short cycle T_s and one with a long cycle T_l . The modulated vibration is represented as the dots in the T_s^{-1} vs. T_l^{-1} plane, and information can be obtained by changing T_s or T_l .

The first challenge is to specify the different-threshold (DT) about frequency for a human's tactile sensor to the modulated vibration when creating the display. Psychological or ERP (eventrelated potential) measurements have been used to estimate the DT on the T_s^{-1} vs. T_l^{-1} plane using a task in which the subject must recognize the difference between an NT (non-target) and a TA(target), where the TA is a more rare stimulus than the NT.

This paper proposes a single-trial analysis for ERP measurements. ERP appears in EEGs (electroencephalogram) when human are performing work, such as recognizing or remembering external stimuli. This study focuses on the ERP's P300 wave that appears when a human cognitively processes an external stimulus. P300 is typically detected using averaged EEG analysis, but the disadvantage of this method is that the EEG wave must be averaged over hours and over time a human concentration tends to deteriorate. However, previous attempts to detect P300 with a single-trial analysis have proved inconclusive. T-test theory was used in the proposed analysis based on the assumption that, on average, the P300's voltage should be higher than that of background activity in a single-trial EEG because P300 has been detected at the top of the plus-voltage in averaged EEGs.

The experiment was conducted with five subjects, and the DTs were individually determined. The subjects were given the task of distinguishing stimuli varied between NT and TA, were NT(T_s^{-1}, T_l^{-1})=(120,8)[Hz] and an optional TA was included.

As a result, the belt-shape figure evident in all five subject model data. In this report, t_A means before-time of begining of the stimulus, and t_B means after-time of that. The shape

is especially remarkable in $300 \leq t_A \leq 500$ [ms]. In short, the effectiveness of manipulating T-test data to detect P300 in single-trial EEGs was assured. In addition, it was discovered that the DT of the proposed method correlates with those reported by previous methods by calculating the correlation coefficients.

According to results, the effectiveness of presuming DT using a single-trial analysis of P300 was assured. Future studies will focus on detecting DT for various tasks using the method proposed in this report, and the practical use of the tactile-display that employs modulated vibration will be developed. Lastly, the authors would like to thank all of the people for their cooperation.

Fig. 2. The Model data of subject (a)

Fig. 3. The subject (a)'s DT

Fig. 1. The T_s^{-1} vs. T_l^{-1} plane

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This study reports the estimation of different-threshold (DT) when humans recognize various modulated vibrations using their tactile sensor. The modulated vibration consists of two frequency components. A psychological or the event related potential (ERP) measurement was used to estimate DT. ERP appears in an electro-encephalogram (EEG) when a human recognizes the information emitted by an external stimulus, and this study detects P300, which is a component of ERP.

This paper proposes a single-trial analysis that uses the T-test, which deviates from the conventional method for detecting P300 called the averaged EEG method. Finally, the proposed method estimates DT. As a result, the effectiveness of the proposed method is assured by estimating DTs on five subjects.

Keywords: tactile sensor, modulated vibration, difference-threshold, P300, single-trial analysis

1. Introduction

This study focuses on the tactile display that uses the modulated vibration⁽¹⁾. Modulated vibration includes two types of single-frequency vibration: one with a short cycle T_s and one with a long cycle T_l . A graphical depiction of the T_s^{-1} vs. T_l^{-1} plane is provided in Fig.1, and the modulated vibration is represented as the dots in the plane. Two-dimensional information can be obtained by changing T_s or T_l .

The first challenge is to specify the different-threshold (DT) about frequency for a human's tactile sensor to the modulated vibration when creating the display. Psychological or ERP (eventrelated potential) measurements have been used to estimate the DT on the T_s^{-1} vs. T_l^{-1} plane using a task in which the subject must recognize the difference between an NT (non-target) and a TA (target)⁽²⁾⁽³⁾, where the TA is a more rare stimulus than the NT.

This paper proposes a single-trial analysis for ERP measurements. ERP appears in EEGs (electro-encephalogram) when a human is performing work, such as recognizing or remembering external stimuli. This study focuses on the ERP's P300 wave that appears when a human cognitively processes an external stimulus. P300 is typically detected using averaged EEG analysis, but the disadvantage of this method is that the EEG wave must be averaged over hours⁽⁴⁾⁻⁽⁶⁾ and over

Fig. 1. The T_s^{-1} vs. T_l^{-1} plane

time a human's concentration tends to deteriorate. However, previous attempts to detect P300 with a single-trial analysis have proved inconclusive⁽⁷⁾⁻⁽⁹⁾.

This paper proposes a new single-trial analysis that employs T-test theory and estimates the DT. The remainder of the paper is organized as follows. The single-trial analysis technique and the method for determining DT is described in Section 2. Section 3 shows the experimental setup and the EEG measurement, and the results and discussion are presented in Section 4. Finally, Section 5 reiterates the conclusions and discusses the future course of study.

2. The Method to Estimate DT

The P300 level used to estimate DT is determined using a single-trial analysis called "cognition-level" in this report.

2.1 The Single-trial Analysis Generally speaking, P300 is detected from the time when the top plus-voltage is specified in an averaged EEG. Thus, it is assumed that, on average, the P300 voltage for a single-trial EEG is higher than that for an EEG that does not

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Fig. 2. Outline of the single trial analysis

have P300⁽¹⁰⁾. This study uses the T-test method for the single-trial analysis, which is then used to estimate DT⁽¹¹⁾.

Figure 2 shows the outline for the single-trial analysis. A single-trial EEG recorded for $2x[\text{ms}]$, from $-x[\text{ms}]$ to $+x[\text{ms}]$, was set to $0[\text{ms}]$ at the start-time for the stimulus. First, two groups (A and B) were obtained from t_A or t_B in the EEG, and the data was recorded for $\tau[\text{ms}]$. $0 \leq t_A \leq x - \tau[\text{ms}]$ and $-x \leq t_B \leq \tau[\text{ms}]$ ranges were fixed μ_A and μ_B were assumed to be the averages of groups A and B, respectively. Second, a T-test is performed on the group and the significance-level for this report was determined to be $\alpha[\%]$. If $\mu_A \neq \mu_B$, $p = 1$ is assumed, otherwise $p = 0$. This relationship is depicted in Eq.(1). p can be expressed in the t_A vs. t_B plane, referred to as the “T-test data” plane. In this paper, a black-dot on is plotted on the plane when $p = 1$, otherwise a white dot is plotted. If P300 appeared in the single-trial EEG, the T-test data would assume the characteristic belt-shape pattern on the t_B axis.

$$p(T_s^{-1}, T_l^{-1}, t_A, t_B) = \begin{cases} 1, & \text{if } \mu_A \neq \mu_B \\ 0, & \text{otherwise} \end{cases} \dots (1)$$

2.2 Estimation of DT Using the experimental data, the model-data that contains the P300's feature in the t_A vs. t_B plane was determined, and this model-data is used to estimate the cognition-level.

Figure 3 shows the method employed to create the model-data. When there are N EEGs that contain P300, stimulus $(T_s^{-1}k, T_l^{-1}k), k = 1, 2, \dots, N$ is introduced and T-test data are obtained as $p_k(t_A, t_B)$. Then, the model-data are obtained as P_β function by using Eq.(2).

The experimental p values are compared with the P_β using the C_L function in Eq.(3). In this paper, $\hat{C}_L$ is employed and smoothed on the T_s^{-1} vs. T_l^{-1} plane when the cognition-level of the single-trial analysis and DT is expressed on the plane. It should be noted that the sampling-frequency is s_f , so a cycle of $s_t (= 1000/f)[\text{ms}]$ is assumed. When $t_A = 4i[\text{ms}]$ and $t_B = 4j - x[\text{ms}]$, then

Fig. 3. Determining the model data

Fig. 4. Determining C_L

$i = 0, 1, \dots, (x - \tau)s_t, j = 0, 1, \dots, (x - \tau)s_t$ in Eq.(3).

$$P_\beta(t_A, t_B) = \begin{cases} 1, & \text{if } \frac{1}{N} \sum_{k=1}^N p_k(t_A, t_B) \geq \beta \\ 0, & \text{otherwise} \end{cases} \dots (2)$$

$$C_L(T_s^{-1}, T_l^{-1}) = \frac{\sum_{i=0}^{(x-\tau)s_t} \sum_{j=0}^{(x-\tau)s_t} p(T_s^{-1}, T_l^{-1}, i, j) \cdot P_\beta(i, j)}{\sum_{i=0}^{(x-\tau)s_t} \sum_{j=0}^{(x-\tau)s_t} P_\beta(i, j)} \dots (3)$$

3. Experiment and Measurement

The experimental setup is displayed in Fig.5. The modulated vibration is output from the PC's D/A-converter (Interface Co:PCI-3310), and then the amplitude is amplified to 16 V by an amplifier. The trigger signal is sent from the D/A-converter to the EEG-instrument (NIHON-CODEN Co:MN-522S) and signals the stimulus starting time. The subject then attaches the PZT (Murata manufacturing Co:77B-21-19RDM-4AD) to his or her forefinger. Each electrode position for the EEG is Cz, Fz, A1, A2. This position refers to the 10-20 system necessary to obtain P300. A1, A2 are the positions required to obtain the base voltage and Fz is linked to ground. The subject wears earplugs and a headphone that eliminates vibration sounds during the experiment. The subjects should be quiet, seated, maintain closed eyes during the EEG measurements.

In this paper, $NT(T_s^{-1}, T_l^{-1}) = (120, 8)[\text{Hz}]$. However, TA is an optional modulated vibration on the plane in Fig.6, whose components T_s^{-1} and T_l^{-1} are set to $40 \leq T_s^{-1} \leq 200[\text{Hz}]$ and $2 \leq T_l^{-1} \leq 20[\text{Hz}]$. The divisions for the T_s^{-1} axis is $10[\text{Hz}]$, while the divisions for the T_l^{-1} axis is $1[\text{Hz}]$.

Figure 7 displays the time schedule for the EEG measurements and the introduction of the stimulus. The stimulus is applied for 2[s]. This report accepts an EEG measured from -1[s] to +1[s], with 0[s] representing the time when the stimulus starts. There is no stimulus during Break-time(BT), which is set for 2[s] in this report. The ratio for supplying the NT or TA stimulus is set to NT:TA=8:2, and the order is random. The sampling-frequency s_f is 250[Hz], and the high-cut and low-cut frequencies are 20[Hz] and 1[Hz], respectively. The subject is instructed to click the PC-mouse when he or she can recognize the difference between NT and TA. This task is referred to as “RB-task” in this paper.

Fig. 5. The experimental setup

Fig. 6. The frequency-region used

Fig. 7. Measurement time schedule

4. Results and Discussion

The experiment was conducted on five subjects (a,b,c,d,e) with a mean age of 22.4 years (S.D.=2.19, range 21-26). One subject was female, and the others were male. Parameters (x, τ, s_t, α , and β) are set to the following values: $x = 1000[\text{ms}]$, $\tau = 200[\text{ms}]$, $s_t = 4[\text{ms}]$, $\alpha = 5[\%]$, $\beta = 0.8$.

4.1 About the Model-data The model-data P_β was determined separately for each subject. Fig.8 shows subject(a)'s P_β . In this paper, two types of EEG groups are used to examine the effectiveness of detecting P300 in a single-trial EEG from T-test data. One group has N single-trial EEGs that can include P300 if the subject was given TA and could answer to RB-task. The other group has N single-trial EEGs that can include P300 if the stimulus was NT. N was set to 60. The result for the former are displayed in Fig.8 (a), and the results for the latter are displayed in Fig.8 (b). It should be noted that the D_β function was assumed using Eq.(4), and its result is presented under the model-data. D_β is P_β 's sum when focus is placed on the t_B axis at t_A . When $t_B = 4j - x[\text{ms}]$, then $j = 0, 1, \dots, (x - \tau)s_t$ in Eq.(4).

According to Fig.8, the belt-shape figure can be found in Fig.8 (a) and a rise of D_β appears in $300 \leq t_A \leq 500[\text{ms}]$. On the other hand, Fig.8 (b) doesn't reflect these features. Fig.9 shows the D_β values for the other subjects (b,c,d,e). The feature in Fig.8 (a) can be found in Fig.9.

$$D_\beta(t_A) = \sum_{j=0}^{(x-\tau)s_t} P_\beta(t_A, j) \dots \dots \dots (4)$$

Fig. 8. The model data for subject (a)

Fig. 9. The results for subjects (b~e) show the distinction of P300 in the model data

Fig. 10. The influence of MRCP (subject(a))

By the way, it is known that P300 appears in an EEG when a human has cognition of an external stimulus. Previous reports had been recording P300 latency using a tactile-stimulus^{(12) (13)}. Thus, two projections can be generated: one feature of Fig.8(a) or Fig.9 indicates P300 in an EEG, and the other Fig.8(b) doesn't. In short, the belt shape figure in the T-test data, like that depicted in Fig.8(a), can be an indication of P300 in a single-trial EEG, and the effectiveness of the single-trial analysis can be assured, which was suggested in Section 2.

There is a concern of that hand's MRCP(movement-related cortical potentials) may have affected EEG. MRCP is the potentials which is related by voluntary movement. Hand's motor area is 7cm away from center on the line which links 2cm behind of Cz and external ear canal. LHM and RHM positins are generally used in the hand's MRCP measurment⁽¹⁴⁾.

In this study, results of experiment without RB-task was compared with the one of the experiment with RB-task. This experiment was done about 2 stimulus discrimination easily, $NT(T_s^{-1}, T_l^{-1})=(120,8)\text{Hz}$, $TA(T_s^{-1}, T_l^{-1})=(40,8)\text{Hz}$ and $N=30$. If MRCP affects EEG, the difference will appear in them. The experiment was conducted on subject(a). The example of this experiment ruslut is shown in Fig.10

The result of experiment without RB-task is showed with bold line, and the other one is showed with fine line. According to Fig.10, the striking difference is not assured in their results.

4.2 About the DT Previous reports have reported a peculiarity in DT on the T_s^{-1} vs. T_l^{-1} plane. The peculiarity is that the cognition level to TA, which is far from NT on the plane, is higher than its level to TA, which is close to NT. A human can easily distinguish between NT and TA because they are widely disparate stimuli. But in the opposite case, such as when TA is close to NT, a human not capable of distinguishing between the two.

In this study, it is assumed that A_L function is calculated using Eq.(5) if the subject answers to RB-task $A_L=1$, otherwise $A_L=0$. $\hat{A}_L$ in which A_L was smoothed on the T_s^{-1} vs. T_l^{-1} plane was used as the cognition-level for the RB-task.

$$A_L(T_s^{-1}, T_l^{-1}) = \begin{cases} 1, & \text{if the subject answered} \\ 0, & \text{otherwise} \end{cases} \quad \dots\dots\dots (5)$$

Figures 11–13 are results for subjects (a), (b), and (d) for the single-trial analysis (a) and psycholical

Fig. 11. The subject (a)'s DT

Fig. 12. The subject (b)'s DT

Fig. 13. The subject (d)'s DT

measurement (b). It is evident from these figures that subject (a)'s D_β is level is high, subject (b)'s D_β is level is low, and subject (c)'s D_β height is a medium level for $300 \leq t_A \leq 500[\text{ms}]$.

Cognition-levels $\hat{C}_L$ and $\hat{A}_L$ are expressed as the black and white colors in the figure. The black color represent a low level, which the white color represents a high level. In other words, the black color indicates that it was difficult for the subject to distinguish between NT and TA, and the white level indicates that the subject could easily distinguish between NT and TA.

The peculiarity cited in previous reports can be observed in Figs.11–13.

4.3 The Effectiveness of the Proposed Analysis The correlation coefficient between $\hat{C}_L$ and $\hat{A}_L$ is

Table 1. Correlation Coefficient R between $\hat{C}_L$ and $\hat{A}_L$

subject	R	subject	R
a	0.47	d	0.6
b	0.34	e	0.48
c	0.68		

generated as an R function by using Eqs. (6)–(10). In this calculation, $T_s^{-1} = 40 + 10i[\text{Hz}]$, $T_l^{-1} = 2 + j[\text{Hz}]$, $i = 0, 1, \dots, n, j = 0, 1, \dots, m$. Then, $n = 17, m = 19$ and $M = n \times m = 323$ is set in this section. The result of R is displayed in Table 1.

$$\overline{C}_L = \frac{1}{M} \sum_{i=0}^n \sum_{j=0}^m \hat{C}_L(i, j) \dots\dots\dots (6)$$

$$\overline{A}_L = \frac{1}{M} \sum_{i=0}^n \sum_{j=0}^m \hat{A}_L(i, j) \dots\dots\dots (7)$$

$$X_{\hat{C}_L}(i, j) = \hat{C}_L(i, j) - \overline{C}_L \dots\dots\dots (8)$$

$$Y_{\hat{A}_L}(i, j) = \hat{A}_L(i, j) - \overline{A}_L \dots\dots\dots (9)$$

$$R = \frac{\sum_{i=0}^n \sum_{j=0}^m X_{\hat{C}_L}(i, j) \cdot Y_{\hat{A}_L}(i, j)}{\sqrt{\sum_{i=0}^n \sum_{j=0}^m X_{\hat{C}_L}^2(i, j) \sum_{i=0}^n \sum_{j=0}^m Y_{\hat{A}_L}^2(i, j)}} \dots\dots\dots (10)$$

Generally, coefficient of correlation R can interpret $|R| > 0.4$ with correlation of the middle degree. According to Table 1, four out of the five subjects were determined to have a medium height R , that is, $\hat{C}_L$ can correlate with $\hat{A}_L$. Thus the analysis proposed in Section2 can be used to estimate DT.

Now, the discussion is focused on the results of subjects (a) and (b) because their R values are lower than that of the other subjects. Subjects (a) and (b) were given another experiment to obtain their averaged EEG. NT and TA for these trials were the same as those specified in Section 3. However, T_s^{-1} or T_l^{-1} of TA is set to a constant 120[Hz] and 8[Hz], respectively.

The result of the averaged analysis is shown in Fig.14 and Fig.15. The V_L function represents the cognition-level to the averaged analysis, and the method employed in previous reports was used to calculate V_L . Fig.14 is the result when T_s^{-1} is constant at 120[Hz], and the result when T_l^{-1} is constant at 8[Hz] is shown in Fig.14. In this paper, if the $\hat{C}_L$ and V_L values correspond in the figures, then V_L is normalized. In the figures, $\hat{C}_L$ is a depicted as a bold black line, and $\hat{V}_L$ is a normal black line. The arrow indicates the position of NT on the T_s^{-1} axis.

According to the figures, it is discovered that $\hat{C}_L$ can correlate with V_L .

Now, R can be calculated between $\hat{C}_L$ and V_L by replacing $\hat{A}_L$ with V_L in Eqs.(7), (9), (10) for each case. In the former case, $T_s^{-1} = 120[\text{Hz}]$, $n = 1, m = 17, M = 17$, and in the latter case $T_l^{-1} = 8[\text{Hz}]$, $n = 19, m = 1, M = 19$.

The result is displayed in Table 2 reveals that almost

Fig. 14. Results of $\hat{C}_L$, V_L when $T_s^{-1} = 120[\text{Hz}]$

Fig. 15. Results of $\hat{C}_L$, V_L when $T_l^{-1} = 8[\text{Hz}]$

Table 2. Correlation Coefficient R between $\hat{C}_L$ and V_L

subject	$R _{T_s^{-1}=120[\text{Hz}]}$	$R _{T_l^{-1}=8[\text{Hz}]}$
a	0.93	0.70
b	0.92	0.36

all R values are high-level. However, subject (b)'s R value for the latter case is low-level and $\hat{C}_L$ in Fig.15 (b) reflects the peculiarity that has been obtained in previous studies rather than V_L .

5. Conclusion

This paper addresses the DT of frequency for a human's tactile sensor about the modulated vibration reported by previous studies that used the psychological or ERP measurement. In this paper, a method that can determine DT using a single-trial analysis of P300 was proposed. T-test theory was used in the analysis based on the assumption that, on average, the P300's voltage should be higher than that of background activity in a single-trial EEG because P300 has been detected at the top of the plus-voltage in averaged EEGs.

The experiment was conducted with five subjects, and the DTs were individually determined. The subjects were given the task of distinguishing stimuli varied between NT and TA, were $\text{NT}(T_s^{-1}, T_l^{-1}) = (120, 8)[\text{Hz}]$ and an optional TA was included.

In Section 4, a belt-shape figure was evident in all five subject model data. This shape is especially remarkable in $300 \leq t_A \leq 500[\text{ms}]$. In short, the effectiveness of manipulating T-test data to detect P300 in single-trial EEGs was assured. In addition, it was discovered that the DT of the proposed method correlates with those reported by previous methods by calculating the correlation coefficients.

According to results, the effectiveness of presuming DT using a single-trial analysis of P300 was assured. Future studies will focus on detecting DT for various tasks using the method proposed in this report, and the practical use of the tactile-display that employs modulated vibration will be developed.

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