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Stimulus Presentation and Analysis Methods for Improving Discrimination Accuracy in P300 Speller

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The brain–machine interface (BMI) has a number of electroencephalogram (EEG) input support tools, including the P300 speller, which uses the event-related potential (ERP), P300. This potential is known to be affected by psychological variables such as the user's attention and discrimination accuracy. In our study, we investigated the effect of fatigue caused by mental load on discrimination accuracy. P300 can be divided into two types: P3a, which occurs in the frontal center, and P3b, which occurs in the parietal center. As there are few studies using P3a as a discrimination method for P300, we included P3a in the discrimination index to check discrimination accuracy. The results showed that the discrimination index using P3a was generally lower than that using P3b in terms of percentage of correct answers, but some participants showed a high percentage of correct answers, which may lead to an improvement in discrimination rate depending on individual characteristics.

1. Introduction

The brain–machine interface (BMI) is a general term for devices that read human brain activity using brain waves or other means, or provide electrical stimulation to the brain, to input and output information between the brain and a computer.(1) In recent years, there has been active research into electroencephalogram (EEG)-based communication and text input tools using this technology. In particular, there are high expectations for the proliferation of communication tools for amyotrophic lateral sclerosis (ALS),(2) a disease that affects motor neurons and presents symptoms such as movement disorders related to muscle weakness, especially in the upper and lower limbs, facial muscle weakness, lip movements, and tongue twisting. The facial muscles are weakened and the lips and tongue become slower, making speech difficult. On the other hand, other cranial nerves often remain intact.(3) For this reason, assistive devices are desirable. There are EEGs that occur in response to specific events, called

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event-related potentials (ERPs). Among these, there is a positive component called P300, which peaks around 300 ms after stimulus presentation in the oddball task and is elicited by changes in attention, cognition, memory, and psychological state.(4) A will estimation system that uses this P300 is a representative.(5)

Briefly, letters are arranged in a matrix on a computer screen and the rows and columns of the matrix are flashed repeatedly. Participants concentrate on the letter they want to select and count the number of times it flashes. When the element containing the letter they want to select lights up, P300 is triggered, which is measured by EEG.(6) This technique is also known as P300 spelling.

It is known that P300 varies with psychological variables, such as the user's attention, and is also affected by discrimination accuracy;(7) the P300 amplitude tends to decrease with age(8) and also tends to decrease when the level of mental fatigue increases before and after the task [9]. In other words, this is another factor that makes discrimination more difficult. We therefore tested whether fatigue affected discrimination accuracy.

P300 can then be divided into two types: P3a, which appears in the frontal/central P300 (related to involuntary attention), and P3b, which appears in the parietal center (related to voluntary attention), and these amplitudes have different characteristics. P3a is perceptually evoked by successive new distractors (such as dog barking and color shape), is evoked by more typical sounds, such as alphabet sound, tends to decrease in amplitude with repetition, and has a greater directional response than P3b. P3b is more likely to be elicited when non-novel repetitive stimuli (such as sounds and letters) are used as distractors with three stimuli and has a better directional response than P3a.(10) Although these differences between stimulus modalities have been investigated in detail, few studies have used P3a as a discriminative index in P300 spellers; thus, we aimed to improve discrimination accuracy by using P3a as a discriminative index in addition to P3b.

For our research, the approval of the Research Ethics Committee of the Department of Human and Artificial Intelligent Systems in the University of Fukui and the consent from each participant had been given.

2. Brain Waves

2.1 EEG

An EEG is a waveform recording of the tiny changes in potential caused by the electrical excitation of nerve cells in the brain, measured by surface electrodes placed on the scalp and amplified by an electroencephalograph.

2.2 ERP

When participants are presented with stimuli, such as light and sound, and perform related tasks, the brain potentials temporally associated with movements such as finger flexion and extension are known as ERPs. Among ERPs, the positive potential P300 appears approximately

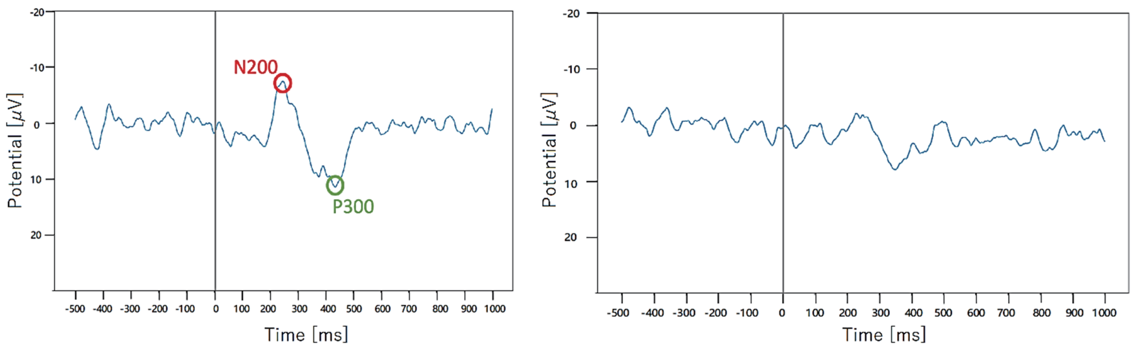
300 ms after stimulus presentation and the negative potential N200 appears approximately 200 ms after stimulus presentation, especially when visual stimuli are presented and attention is focused on a specific event. The occurrence of event-related potentials is usually confirmed by the appearance of P300.(11)

Figure 1 shows the EEG response to a specific event. The vertical axis shows the potential [μV] and the horizontal axis shows the time [ms]. The vertical bar at time 0 [ms] indicates the start of stimulus presentation. Amplitudes called N200 and P300 can be seen when a specific event is responded to (left panel), while large amplitudes are not seen when a specific event is not responded to (right panel). Note that by checking P300 and N200, it is possible to determine the event to which the subject is attending.

Figure 2 shows the reactions for P3a and P3b of P300 described above.

2.3 Oddball task

The oddball task is a task in which two or more stimuli with different frequencies are presented in random order and participants are asked to count the number of times the stimuli with low probability appear. In general, stimuli that occur with high probability are called standard stimuli and stimuli that occur with low probability are called target stimuli.(12)



(a) (b)

Fig. 1. (Color online) ERPs (a) in response to an event and (b) in the absence of response.

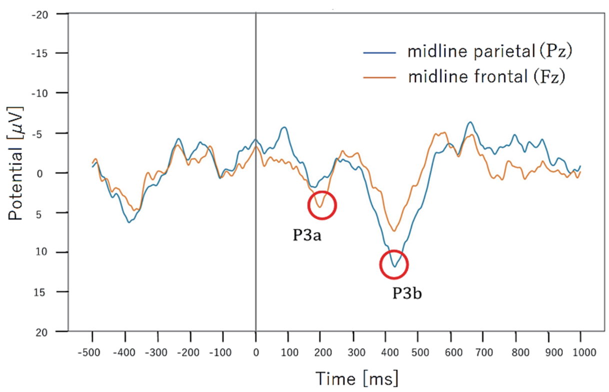


Fig. 2. (Color online) Characteristics of P3a and P3b in ERPs.

3. EEG

3.1 EEG

In this study, the EEG is obtained by scalp EEG. This involves attaching electrodes to the scalp and using an electroencephalograph to record changes in potentials in different areas of the brain. The electrode configuration was set up according to the International 10-20 method recommended by the International EEG Society, as shown in Fig. 3. Nine electrodes, Fz, Cz, Pz, C3, C4, F3, F4, P3, and P4, were selected for this measurement and the experiment was carried out. The reference electrode derivation method (binaural coupling reference method) was used and the left ear (A1) and the right ear (A2) were set as reference electrodes. As shown in Fig. 4, a reference was placed in the middle of the forehead in front of the face, and a ground was placed to the left of the reference, and electrodes for eyes were placed to remove artifacts such as blinking and eye movements that may mix with the EEG.

3.2 Specifications and recording settings of the device used in the experiment

The specifications and recording settings of the bioamplifier (Polymate) used for the EEG measurements in this experiment are described.

The resolution of the Polymate is as follows.

- A/D converter: 16 bits.

Recording conditions are as follows.

- Sampling frequency: 500 Hz.
- Notch filter: 60 Hz.

The target EEG frequency range is 0.5 to 30 Hz.

- Time constant: 0.3 s, Low cutoff: 0.53 Hz, High cutoff: 30 Hz.

Fig. 3. (Color online) Placement of EEG electrodes.

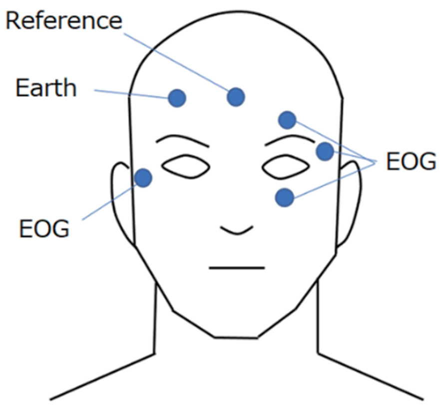


Fig. 4. (Color online) Placement of electrodes on the face.

Electro-oculography (EOG) should be measured simultaneously with EEG measurements because it introduces artifact noise into the EEG signal. The following filters were set in the EOG channel because the frequency band of EOG can be detected in the range of 5–100 Hz.

- Time constant: 0.03s, Low cutoff: 5.3 Hz, High cutoff: 100 Hz.

3.3 Electrodes and skin treatments used in the experiment

A portable, versatile bioamplifier (TEAC, PolymateAP1532) was used as the EEG measurement device in the experiment. The electrodes used for EEG and electro-oculogram measurements were as follows.

- Plate electrode Ag/AgCl, 11 mm diameter (inner diameter: 7 mm), manufactured by Nihon Kohden Co.

  The following exfoliation and cleansing products were used.
- For exfoliation: Skinpure, manufactured by Nihon Kohden Co.
- For skin cleansing: Ethanol (99.5%), manufactured by Amaksu Chemical Industries.

The following electrode paste was used for electrode application:

- Weaver and Company Ten20 EEG Conductive Paste

3.4 Procedure for applying EEG electrodes

The main methods of EEG recording are the unipolar electrode recording method, the bipolar electrode recording method, and the central reference electrode method. The unipolar derivation electrode recording method is performed on the head with respect to a point electrically close to zero (the earlobe). The bipolar derivation method records the potential difference between two points on the head. The average reference electrode method is a method in which several active electrodes placed on the scalp are connected to a single point and this point is used as the reference electrode for recording. The unipolar derivation method is used in this experiment.

For more accurate EEG measurements, it is important to minimize the contact resistance between the electrodes and the scalp and to minimize contamination by artifacts. The contact resistance of the electrodes is checked by AC impedance measurement. Skin pretreatment should be carried out so that the impedance of each electrode is less than 10 kΩ.

3.5 Experimental scene

The experiment was conducted in a shielded room because the EEG is very weak and electromagnetic objects such as light cables and PCs can easily be mixed in as noise. The participants were asked to sit on chairs in the shielded room and the experiment was conducted in a comfortable position. During each trial of the task during the experiment, the participants were instructed to avoid movement and blinking as much as possible so as not to interfere with the EEG measurement. Figure 5 shows a scene from the experiment. The distance between the subject and the screen was 100 cm. The visual stimulus presentation software "Presentation" (Neurobehavioural Systems) was used to present the images.

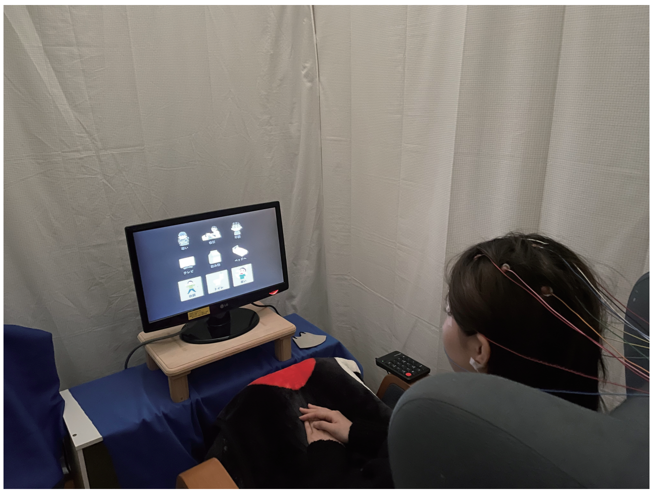


Fig. 5. (Color online) EEG experiments in a shielded room.

3.6 Control of condition of participants in this study

All participants were healthy university students in the field of engineering. To control their condition, we asked them to get enough sleep the day before, refrain from excessive exercise or work, eat breakfast and lunch on the day of the experiment, and perform the experiment in the afternoon.

4. Methods for Identification of Selection Events

4.1 Shaping of EEG data

A threshold of ±100 μV was set for the measured data of the eye potentials, and data exceeding the threshold were removed to suppress the effects of eye movements and blinks on the waveform of the event-related potentials. The event-related potentials had to be calculated at the beginning of a specific event, so a trigger was entered at the time of the flash from the presentation (signal presentation software) so that the data could be cut out at the time of the flashes of the rows and columns of the experimental screen and recorded together with the EEG data. When the data were analyzed, the trigger start position was found by automatic processing by the program, and the trial section in each task was automatically cut out.

4.2 Derivation of event-related potentials

At the start of each event, the EEG data associated with each event are summed over several dozen times and averaged. This cancels out the background EEG and allows the event-related brain potentials to be extracted.

4.2.1 Methods of additive averaging

Additive averaging is performed according to Eq. (1).

$$\mu_s = \frac{1}{N}\sum_{n=1}^{N} x_{ns}, \text{ from } s = -250 \text{ to } s = 500 \tag{1}$$

μ_s: EEG data after additive averaging
μ_{ns}: EEG data before additive averaging
N: Number of data to be additionally averaged
n: Number of data
s: Number of step time data with stimulation start as 0

The data interval subject to additive averaging is −500 ms to 1000 ms and the sampling frequency is 500 Hz, so the step size is −250 to 500. As the number of additions increases, the random noise is cancelled out and disappears, resulting in a stable waveform. In the present study, the number of additions was set at 20. For some participants, the number of additions could be less than 20 due to the effect of removing the electrical data from the eye.

4.2.2 Baseline alignment

In the additive average waveform, the baseline is adjusted by subtracting the average potential before stimulus presentation. The average potential $OFFSET_n$ of the baseline interval is obtained as

$$OFFSET_n = \frac{1}{250}\sum_{s=-250}^{0} x_{ns}, \text{ from } n = 1 \text{ to } n = N. \tag{2}$$

The N-adjusted average as in Eq. (3) is then subtracted from the average potential of the baseline section to give the baseline-aligned waveform A_i.

$$A_i = \mu_s - OFFSET_n, \text{ from } s = -250 \text{ to } s = 500 \tag{3}$$

The amplitude of event-related potentials after stimulus presentation is clarified by the above baseline matching procedure.

4.3 Definition of indicators to be used to distinguish between selection events

For the discrimination method for a selection event trial, one stimulus is assumed to be the target stimulus and the other stimuli are assumed to be the standard stimuli, and an additive averaging procedure is performed to calculate the event-related potentials. Features are then computed on the basis of the indices used as discrimination criteria for the selection event. This is performed for all nine stimuli and the target stimulus is discriminated using the indices shown below.

From the ERP waveforms obtained using the procedure described in Sect. 4.2, the features shown in Fig. 6 were obtained and indicators were created. The waveforms measured at sites such as Pz for indices 1–6, Fz for index 7, and Cz for index 8, shown below, were used.

The vertical axis of the figure is potential (μV), with the downward direction being positive. The horizontal axis is time [ms]. The vertical bar at time 0 [ms] indicates the start of stimulus presentation. For indices 1–6, we focused on N200 and P300; for N200, we focused on the case of the smallest potential, i.e., the peak amplitude between 100 and 300 ms after stimulus presentation. For P300, we focused on the highest peak amplitude potential between 250 and 700 ms after stimulus presentation. We also focused on the peak latency at this time.

- Indicator 1

P300 is characterized as a peak in amplitude with a maximum potential between 250 and 700 ms after stimulus presentation. The potential of this peak is expressed as V_{P300} and used as indicator 1. The value of indicator 1 is considered to be maximum when the stimulus is a target stimulus.

- Indicator 2

N200 is characterized as a peak in amplitude with a minimum potential between 100 and 300 ms after stimulus presentation. The potential of this peak is expressed as V_{N200} and used as indicator 2. The value of indicator 2 is considered to be minimum when the stimulus is a target stimulus.

- Indicator 3

The potential difference between V_{P300} and V_{N200} is taken as V_{target} and calculated using Eq. (4). This is index 3 and the stimulus with the highest value is discriminated as the target stimulus.

$$V_{target} = V_{P300} - V_{N200} \tag{4}$$

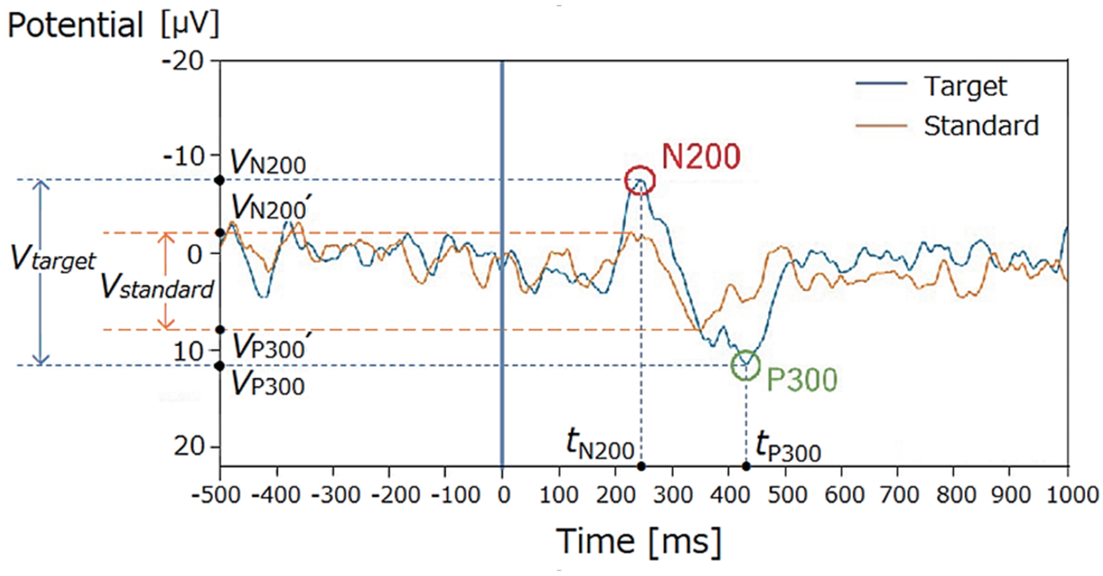


Fig. 6. (Color online) Features for index creation in ERP waveforms.

- Indicator 4

For the ERP waveform used as the standard stimulus, the potential difference between V_{P300}' and V_{N200}' is taken as $V_{standard}$, as in Indicator 3. The difference in amplitude between the target and standard stimuli, V_d, is then calculated as in Eq. (5). Indicator 4 discriminates the stimulus with the largest V_d value among the other stimuli as the target.

$$V_d = V_{target} - V_{standard}, \left(V_{standard} = V_{P300}' - V_{N200}'\right) \quad (5)$$

- Indicator 5

The peak latency of P300 is defined as t_{p300}, which is indicator 5. The stimulus with the lowest value is identified as the target stimulus.

- Indicator 6

The peak latency of N200 is V_{N200} and the time difference between the peak latencies of N200 and P300 is t_{PN}, as in Eq. (6). This is index 6, and the stimuli for which this value is the largest or smallest are identified as the subject's chosen event.

From Sect. 5 onwards, indicator 6 (large) indicates that the stimulus with the largest T_{PN} value is discriminated as the target stimulus, whereas indicator 6 (small) indicates that the stimulus with the smallest t valueis discriminated as the target stimulus.

$$t_{PN} = t_{P300} - t_{N200} \quad (6)$$

5. Preliminary Experiments: Exploring Stimulating Images

EEG-based intention estimation using the P300 speller is based on the following principle: nine illustrations of three rows by three columns are prepared, as shown in Fig. 7, and the elements of the rows and columns are flashed one after the other, and the subject is asked to count the number of times that the flashed part contains a target in his or her mind. The target, i.e., the image selected by the subject, is estimated from the relationship between the presented stimulus and the EEG. In our experiments, the stimulus image is flashed 75 times per set of oddball tasks.

The method of presenting the stimulus images should be adapted according to the age of the subject and the presence or absence of disease in order to improve viewing comfort and allow the subject to perform the task without stress. In this study, healthy university students were the participants, and we investigated the effects of the method of presenting the stimulus images on discrimination accuracy in terms of blink order and display interval through the four preliminary experiments described below, and adjusted the parameters to make the images easier to see for the present group of participants.

Fig. 7. (Color online) Example of stimulus image presentation.

5.1 Preliminary experiment 1: Investigation of flashing sequence of stimulus images

The images are presented in random and fixed orders with respect to the order in which the rows and columns are flashed, and the rates of correct discrimination of the target stimuli due to differences in the flashing patterns are compared.

The experimental details were as follows.

- The participants were shown two types of picture, random and sequential, four times in succession.
- The number of flashes per stimulus was set to 75, the stimulus presentation time to 1.0 s, and the stimulus interval time to 1.0 s.
- The probability that a row or column containing the target would flash was set to approximately 1/6.

Arrange 9 illustrations in a 3 × 3 grid. Place the content related to physical conditions in the four corners, those with high urgency in the middle of rows 1 and 3, and those related to operations and movements in row 2. To reduce selection errors in adjacent images, images with similar contents were separated, and the oddball task was performed six times per subject. The participants were three healthy university students (mean age: 22.9; *SD* = 1.0), and the recognition results are shown in Table 1.

The participants were asked to answer the following questionnaire items on a 5-point scale (5: excellent, 4: great, 3: good, 2: fair, 1: poor). The average score for each item is also shown.

(1) Is predetermined order better than random order? 4.0

The free text of the questionnaire is as follows.

- In the case of order, it was monotonous and made me sleepy.
- In the case of order, they could not concentrate and count to the end because they already knew the number of times.
- In the case of randomness, they made counting errors when the target stimulus appeared randomly.
- In the case of chance, they were surprised when the target stimulus lights up in succession.

All three participants responded more correctly to the random order from the EEG. In question (1) of the questionnaire, all three participants answered that the fixed order was better than the random order, but in their free descriptions, some were critical, saying that the fixed order was monotonous and interrupted their concentration.

Table 1
Results of Preliminary Experiment 1.

	Flashing pictures in fixed order		Flashing pictures in random order	
	Average accuracy rate (%)	Standard deviation	Average accuracy rate (%)	Standard deviation
Indicator 1	33.3	38.2	66.7	28.9
Indicator 2	16.7	28.9	25.0	25.0
Indicator 3	41.7	38.2	50.0	25.0
Indicator 4	50.0	25.0	66.7	28.9
Indicator 5	0.0	0.0	0.0	0.0
Indicator 6-1 (large)	25.0	25.0	0.0	0.0
Indicator 6-2 (small)	8.3	14.4	0.0	0.0

Although it would be expected that the correct response rate would be higher when the EEG was displayed in random order, a t-test was performed on the mean amplitude of the EEG to the target stimulus for both orders and it was significantly ($p < 0.05$) greater, so it is considered to be effective in making judgments.

5.2 Preliminary Experiment 2: Investigation of time intervals for presentation of stimulus images

In Preliminary Experiment 2, three time intervals of 500, 250, and 125 ms were prepared for the presentation of the stimulus images, and the oddball task was performed six times per subject. The participants were three healthy university students (mean age: 22.9; *SD* = 1.0), and the recognition results are shown in Table 2.

Preliminary Experiment 2 showed that the discriminative correct response rate was higher when the time interval between the stimulus images was 250 ms. After the experiment, the participants were asked to answer the following questionnaire items.
(1) Regarding the stimulus pictures, there were three types of blink duration. Please circle the appropriate one. (・500 ms, ・250 ms, ・125 ms)

Two participants responded that 250 ms was good. There were no specific responses for free description.

5.3 Preliminary experiment 3: Investigation of stimulus time intervals for stimulus images

Two types of time interval were prepared for stimulus presentation: a constant interval (500 ms) and a random interval (varying between 125 and 500 ms). The oddball task was performed four times, and the target stimuli were discriminated from the EEG data at that time, and the effects of the different time intervals on the percentage of correct responses were investigated. The participants were three healthy university students (mean age: 22.9; *SD* = 1.0), and the recognition results are shown in Table 3.

Table 2
Recognition results for different time intervals of stimulus presentation.

	500 ms		250 ms		125 ms	
	Average accuracy rate (%)	Standard deviation	Average accuracy rate (%)	Standard deviation	Average accuracy rate (%)	Standard deviation
Indicator 1	50.0	70.7	75.0	35.4	55.2	28.0
Indicator 2	0.0	0.0	75.0	35.4	55.2	28.0
Indicator 3	50.0	70.7	100.0	0.0	50.0	70.7
Indicator 4	50.0	70.7	100.0	0.0	50.0	70.7
Indicator 5	25.0	35.4	0.0	0.0	0.0	0.0
Indicator 6-1 (large)	0.0	0.0	0.0	0.0	0.0	0.0
Indicator 6-2 (small)	50.0	70.7	0.0	0.0	0.0	0.0

Table 3
Percentage correct for different time intervals between stimulus presentations.

	Constant interval (500 ms)		Random interval (varying from 125 to 500 ms)	
	Average accuracy rate (%)	Standard deviation	Average accuracy rate (%)	Standard deviation
Indicator 1	50.0	0.0	50.0	70.7
Indicator 2	0.0	0.0	0.0	0.0
Indicator 3	0.0	0.0	75.0	35.4
Indicator 4	0.0	0.0	50.0	0.0
Indicator 5	25.0	35.4	0.0	0.0
Indicator 6-1 (large)	25.0	35.4	0.0	0.0
Indicator 6-2 (small)	0.0	0.0	25.0	35.4

Preliminary Experiment 3 showed that for two participants, some indicators of a higher percentage of correct responses were obtained when the time interval of stimulus presentation was random. The participants were asked to answer the following questionnaire items on a 5-point scale (5: excellent, 4: great, 3: good, 2: fair, and 1: poor). The average score for each item is also shown.

(1) Are random intervals of stimulus time intervals for the stimulus video better than fixed intervals of stimulus time intervals? 4.0

The free text of the questionnaire is as follows.

- Regarding the random change, there were cases where the user was confused when the change was extreme.

When this participant's experimental results were examined, he often responded strongly to nontargets, which resulted in a lower rate of detecting the target.

Another subject responded:

- I did not understand the difference between random and fixed cases.

In Preliminary Experiment 4, the parameters were set to avoid extreme changes and the same experiment was run again.

5.4 Preliminary experiment 4: Investigation of time intervals between presentation of stimulus images

A total of six experiments were performed with two different stimulus time intervals: one with a constant stimulus interval time of 250 ms and the other with three random values of 200, 250, and 300 ms. The target stimuli were discriminated from the EEG data measured during the experiments, and the discriminant correct response rates for the different stimulus interval times were compared. The participants were the same as in Preliminary Experiment 3.

In the present results, between the random and constant stimulus presentation interval time cases, there was no significant difference in discriminative correct response rate. The reason for this is that the participants did not notice the randomness of the stimulus interval time because the interval times were 200, 250, and 300 ms, and the participants did not notice the randomness because the interval time was small. It was decided to keep the stimulus interval time constant and use 250 ms in the future because some participants found it easier to count when the random time range was increased as in Experiment 3, while others were confused.

6. Effect of Mental Strain on Accuracy of Identification

We investigated whether the stimulus presentation methods examined in Sect. 5 would have an effect on the accuracy of discrimination of choice events in the presence and absence of mental stress.

6.1 Experimental methods

The participants were seven healthy students (mean age: 23.3 ± 1.0 years) who were subjected to the two different experiments described in Sects. 6.1.1 and 6.1.2. These two experiments were performed on different days.

6.1.1 Oddball task

The stimulus images were presented in the three-row, three-column display of the P300 speller (Fig. 7), with each row or column flashing. The number of stimulus presentations was set to 75, the stimulus presentation time to 500 ms, and the stimulus interval time to 250 ms.

The participants were asked to count the number of flashes of a prespecified target image (target stimulus). During counting, the participants were instructed to fixate on the target stimulus. The EEG was recorded throughout the task. The oddball task was performed a total of six times.

6.1.2 Calculation task as mental strain

As a mental strain, the participants performed a two-digit addition task for 15 min, as shown in Fig. 8, in which they were presented with a two-digit addition task on the monitor, and when they had worked out the answer, they had to press a button to move on to the next problem. They were then asked to complete the oddball task described in Sect. 6.1.1, as shown in Fig. 9.

6.2 Experimental results

The results of the experiment are summarized in Table 4. All seven participants with mental strain showed slightly fewer discriminative correct responses to the target stimuli on most indices. Some participants answered in the post-experiment questionnaire that they were fatigued by the 15-min calculation task and that they felt drowsy during the oddball task after the calculation task, suggesting that they were more fatigued in the experiment with mental strain than without it, but there was no significant difference in recognition accuracy Therefore, it is considered that the mental strain does not have much effect on the recognition rate.

Fig. 8. Example of a calculation task to present on the screen.

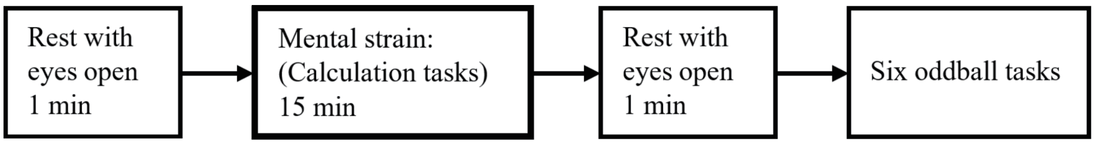


Fig. 9. Experimental procedures for mental stress.

Table 4
Percentage correct for different time intervals between stimulus presentations.

	Without mental strain		With mental strain	
	Average accuracy rate (%)	Standard deviation	Average accuracy rate (%)	Standard deviation
Indicator 1	54.8	34.3	52.3	20.1
Indicator 2	35.7	17.8	34.7	20.0
Indicator 3	54.8	24.9	48.5	24.5
Indicator 4	52.4	26.2	48.1	23.6
Indicator 5	9.5	16.3	17.0	9.7
Indicator 6-1 (large)	9.5	13.1	9.1	5.4
Indicator 6-2 (small)	16.7	23.6	29.4	21.1

6.3 Discussion

In this study, eight indicators were created on the basis of the characteristics of event-related potentials, and the selected event was discriminated for each indicator. First, in preliminary experiments, it was found necessary to adjust the order in which the rows and columns of the P300 speller flashed, as well as the sensation and timing of the flashing, in order to make it easier to use.

In the comparison experiment between the case where the participants were given a mental load and the case where they were not given a mental load, it was confirmed that there was no difference in discrimination accuracy between such cases, although the participants did feel fatigue, and therefore, there was no significant effect observed.

7. Additional Indicators Based on ERP for P3a and P3b

7.1 Additional indicators based on P3a

Indicators 1 to 6 have used the ERP waveform of P3b (see Fig. 6) recorded at the location of Pz in Fig. 3. To improve the accuracy of discrimination of selected events, a new use is made of the ERP waveform of P3a (see Fig. 6) recorded at Fz and Cz in Fig. 3.

- Indicator 7

For the ERP waveform at site *Fz* in Fig. 3, V_{P300_Fz} with the largest potential, i.e., the peak amplitude 180–300 ms after the presentation of the target stimulus P3a (see Fig. 6), is determined and used as Indicator 7. The stimulus with the highest value is identified as the target stimulus.

- Indicator 8

For the ERP waveform at the *Cz* site in Fig. 3, V_{P300_Cz} with the largest peak amplitude potential 180–300 ms after the presentation of the target stimulus P3a (see Fig. 6) is determined and used as indicator 8. The stimulus with the largest value is discriminated as the target stimulus.

7.2 Experimental results

The results of the analysis of seven subjects using the no-load data from Sect. 6 are shown in Table 5. First, for indicators 1–6 using P3b, indicators 1–4 were generally considered valid.

However, the percentage of correct answers was lower for two subjects. For indicators 7 and 8 using P3a, the percentage of correct answers could be increased for subject 1. This may indicate which indicators are effective according to individual characteristics.

7.3 Discussion

Indicators 1 through 6 are all related to P3b. As shown in Fig. 6, indicators 1 and 2, which use the peak of the P300 and N200 response potentials in the target stimulus as the feature value, and indicator 3, which uses the peak-to-peak potential as the feature value, are effective when the target stimulus responds significantly, and the discrimination accuracy rate is also considered to be high.

Table 5.
Percentage of correct answers for each indicator for seven subjects.

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7	Average accuracy rate (%)	Standard deviation
Indicator 1	0.0	**83.3**	**66.7**	16.7	**50.0**	**83.3**	**83.3**	**54.8**	34.3
Indicator 2	16.7	**50.0**	33.3	33.3	16.7	33.3	**66.7**	35.7	17.8
Indicator 3	16.7	**83.3**	**50.0**	33.3	**50.0**	**66.7**	**83.3**	**54.8**	24.9
Indicator 4	33.3	**83.3**	33.3	16.7	**50.0**	**66.7**	**83.3**	**52.4**	26.2
Indicator 5	33.3	0.0	0.0	0.0	0.0	0.0	33.3	9.5	16.3
Indicator 6-1 (large)	0.0	0.0	33.3	16.7	0.0	16.7	0.0	9.5	13.1
Indicator 6-2 (small)	16.7	0.0	16.7	0.0	0.0	16.7	**66.7**	16.7	23.6
Indicator 7	0.0	0.0	33.3	16.7	**50.0**	16.7	0.0	16.7	19.2
Indicator 8	**66.7**	0.0	**66.7**	16.7	**50.0**	16.7	16.7	33.3	27.2

Items with more than 50% correct answers are shown in bold.

On the other hand, when the amplitude of the standard stimulus also increases, indicator 4, which uses the amplitude difference between the target and standard stimuli as a feature, is not considered effective.

In addition, indicators 5 and 6, which use the peak latency of P300 and N300 as a feature, are not considered to be as effective because the latency did not differ much between the target and standard stimuli. Indicators 7 and 8 are both P3a and characterize the peak of the P300 response potential of the target stimulus. The rate of correct discrimination was lower in most subjects, possibly owing to the slowing down of habituation by repetition, which is the established theory.

8. Conclusion

In this study, eight indicators were created on the basis of the characteristics of event-related potentials, and the selected event was discriminated for each indicator. First, in preliminary experiments, it was found necessary to adjust the order in which the rows and columns of the P300 speller flashed, as well as the sensation and timing of the flashing, in order to make it easier to use.

In the comparison experiment between the case where the subjects were given a mental load and the case where they were not given a mental load, it was confirmed that there was no difference in discrimination accuracy between such cases, although the participants did feel fatigue, and therefore, there was no significant effect observed.

The percentage of correct responses to discriminative indices using P3a and P3b was generally lower for discriminative indices using P3a than for those using P3b, which has been used in the P300 speller for some time. This finding was supported by the fact that the P3a response is blunted by habituation due to repetition, as explained in previous studies, and that P3b is superior to P3a for directional responses to non-novel repetitive stimuli. However, in some subjects, P3a showed a higher percentage of correct responses than P3b, suggesting that some individual characteristics may lead to improved discrimination rates.

The recognition accuracy of each of the eight indicators tended to vary from subject to subject, but it is thought that recognition accuracy may be improved in the future by using indicators that are effective for each subject, i.e., by tailoring them to the user. It is also considered effective to weigh these indicators and discriminate them in a composite manner by expressing each indicator in a linear combination formula.

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