Brain-Computer Interface Using fNIRS Waveforms when Recalling the Experience of Eating Savory and Spicy Instant Noodle

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***Abstract*—In this study, we propose a recall method and a signal processing method to achieve intentional BCI output by a user by changing the fNIRS waveforms from the central part of the forehead by having the user recollect the experience of eating savory and spicy instant noodle. In other words, we focused on the differences in the amount of change in oxygenated hemoglobin concentration at the upper center of the forehead and the amount of change in oxygenated hemoglobin concentration lower center of the forehead when recollecting the experience of eating led to intentional BCI output. When the amount of change in oxygenated hemoglobin concentration in the lower center of the forehead changes significantly more than the amount of change in oxygenated hemoglobin concentration in the upper center of the forehead, BCI output occurred. Results of a series of experiments, our best output result for 109 intended BCI outputs was 104 successful outputs (i.e., a success rate of 94.5%). In comparison, there were four outputs when output was not intended, and four instances of no output when output was intended. We believe this suggests that we can execute highly accurate BCI output by adjusting the time intervals when acquiring the difference value from the set time intervals, and by adjusting the thresholds of the cumulative value of the difference between the probes that measure the difference value of the set time interval for the amount of change in oxygenated hemoglobin concentration lower center of the forehead and that measure the difference value of the set time interval for the amount of change in oxygenated hemoglobin concentration upper center of the forehead.**

***Index Terms*—brain-computer interface, fNIRS, recall of eating experience, spicy instant noodle**

I. Introduction

In recent years, research using brain function measurement has been surging. Research has not been limited to medical diagnoses but has been applied to a variety of fields, including everything from brain science to engineering uses. As an example of engineering use, there is research related to Brain-Computer Interface (BCI). BCI is the general name used for systems that control an external device, e.g., a wheelchair, by using brain activity resulting when a user wearing a brain function measurement device recalls a specific thing [1]-[4]. By using such systems, users can control external devices without having to move their bodies [5], [6]. In developing these systems, the authors focused on estimating the output start time of one type of BCI, i.e., the estimated time when the user intended to move the external device.

The researchers' group chose a functional Near-Infrared Spectroscopy (fNIRS) device to measure brain activity. fNIRS devices can be expected to limit the effect of brain activity measurement when there is only small body movement, such as when measuring brain activity during rehabilitation [7]-[9]. We decided to use the experience of eating savory and spicy instant noodle as the recollected content. The reasoning for this is that Nakai, *et al.* [10] noted that recalling the experience of being presented with Tabasco® sauce caused changes in brain activity.

As a preliminary experiment, we had one subject recall various types of oral stimulation, such as sour and spicy. By verifying the recollected content that could change the fNIRS waveform, we found that the ch in the central frontal lobe could be changed in many cases when recollecting the eating of savory and spicy instant noodle. Therefore, this paper uses the situation of eating savory and spicy instant noodle as the recollected content used for BCI. We are proposing a system that can output BCI controls within the specified time from the fNIRS waveforms produced under those circumstances.

II. Experiments

In this study, we had one subject recollect eating savory and spicy instant noodle in about two-minute intervals. We thoroughly explained the contents of the experiment to the subject beforehand and conducted the experiment with the subject's consent. We had the subject sit down and attached the OEG-17APD (made by Spectratech Inc.) which is the frontal lobe fNIRS to the subject's forehead. The attachment location of the device is shown in Fig. 1. Regardless of the time of day, the room was illuminated with fluorescent lights. With regard

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to the recollection timing, we allowed two minutes from the start of the first recollection to the start of the next. However, we basically left up the recollection start time to the subject. The recollection end time was the time when it was believed that the subject had a sufficient recollection or the time when we believed that the subject was tired of recollecting. In other words, the recollection time was freely set by the subject. The measurement time was concluded when the subject started to feel fatigued or sleepy. In this study, we conducted 25-minute measurements in 13 trials for a total of 109 recollections in all of the trials. Fig. 2 shows an example of the recollection time schedule during a trial and the fNIRS waveforms corresponding to the time.

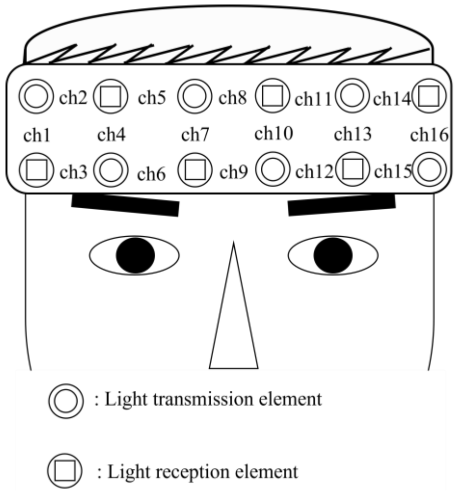

Figure 1. fNIRS device positioning relative to the face.

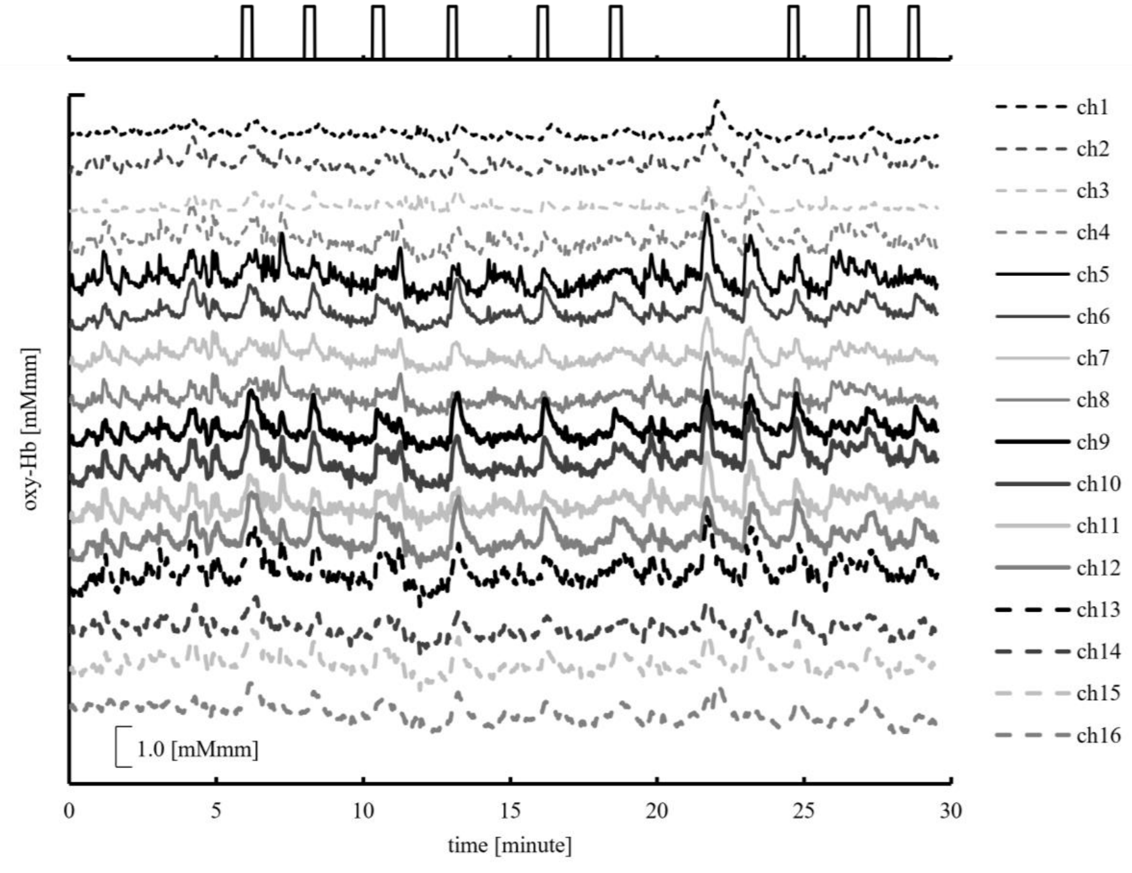

Figure 2. An example of fNIRS waveform when recollecting within the timeframe.

III. ANALYSIS

To output BCI from the fNIRS waveforms, we focused on the amount of change in oxygenated hemoglobin concentration. In Fig. 2, when the subject is not recollecting, i.e., when BCI is not being output, the waveforms of ch5, ch8, and ch9 at the center of the forehead have the same shape. In comparison, when the subject is recollecting, i.e., when the subject is trying to output BCI, the waveforms for the amount of change in oxygenated hemoglobin concentration in ch9 is far greater towards the positive than the amount of change in oxygenated hemoglobin concentration for ch5 and ch8. We used this feature for output.

A. Acquiring the Time Difference Value

To acquire the size difference in waveforms, we acquired the difference value in the amount of change in oxygenated hemoglobin concentration of ch5, ch8, and ch9 at n time before data and at the current time. If the amount of change in oxygenated hemoglobin concentration for ch5, ch8, and ch9 at the current time t are $oxy_5(t)$, $oxy_8(t)$, and $oxy_9(t)$, then the time difference value $diff_5(t)$, $diff_8(t)$, and $diff_9(t)$ are as follow:

$$diff_5(t) = oxy_5(t) - oxy_5(t-n)$$

$$diff_8(t) = oxy_8(t) - oxy_8(t-n)$$

$$diff_9(t) = oxy_9(t) - oxy_9(t-n)$$

As an example, when n=8, Fig. 3 shows the change over time of the time difference value.

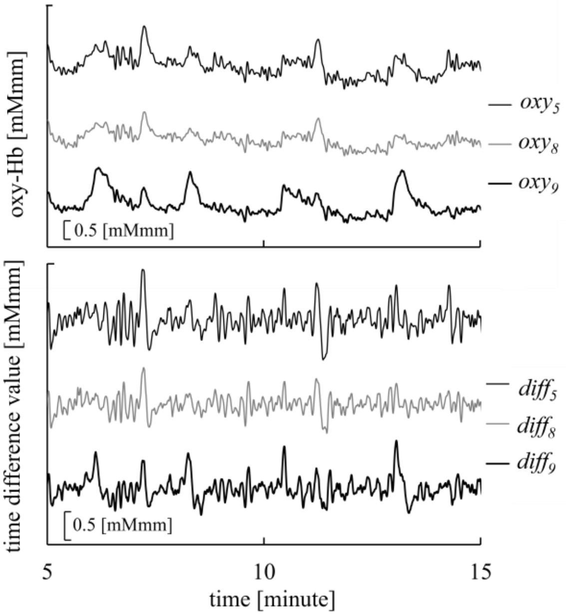

Figure 3. An example of fNIRS waveform of ch5,8, and 9 (top) and the time difference values calculated from them (bottom).

B. Acquiring Features Using the Integrated Value of the Time Difference Value

In the waveforms produced when trying to output BCI, the waveforms for the amount of change in oxygenated hemoglobin concentration in ch9 changes significantly in the positive direction. Therefore, by calculating the larger the value, the larger the change in the waveforms continue. So, when the time difference value $diff_9(t)$ of ch9 is greater than 0, then the integrated values of $area_5(t)$, $area_8(t)$, $area_9(t)$ are as follow:

$$area_5(t) = area_5(t-1) + diff_5(t)$$

$$area_8(t) = area_8(t-1) + diff_8(t)$$

$$area_9(t) = area_9(t-1) + diff_9(t)$$

When $diff_9(t)$ is 0 or smaller:

$$area_5(t) = 0$$

$$area_8(t) = 0$$

$$area_9(t) = 0$$

Fig. 4 shows an example of the change over time of the integrated value of the time difference value.

For the integrated value of each ch, when the value of $area_9(t)$ is greater than the threshold *thresh* compared with the values of $area_5(t)$, and $area_8(t)$, then $result(t)$=1 is output as the BCI. In other words, when feature values $area\_diff_5(t)$ and $area\_diff_8(t)$ for BCI output are as follows:

$$area\_diff_5(t) = area_9(t) - area_5(t)$$

$$area\_diff_8(t) = area_9(t) - area_8(t)$$

Then,

if ($area\_diff_5(t)>thresh$ && $area\_diff_8(t)>thresh$)

$result(t)$=1

However, because this study only focuses on the output start time, the final output $flag(t)$ is as follows:

if ($result(t)$ == 1 && $result(t)$ == 0)

$flag(t)$=1

As an example, Fig. 5 shows when n=8 and *thresh*=1.7, and the resulting intended output time, the waveforms of the amount of change in oxygenated hemoglobin concentration at that time, the waveforms of features $area\_diff_5(t)$ and $area\_diff_8(t)$, and the output results.

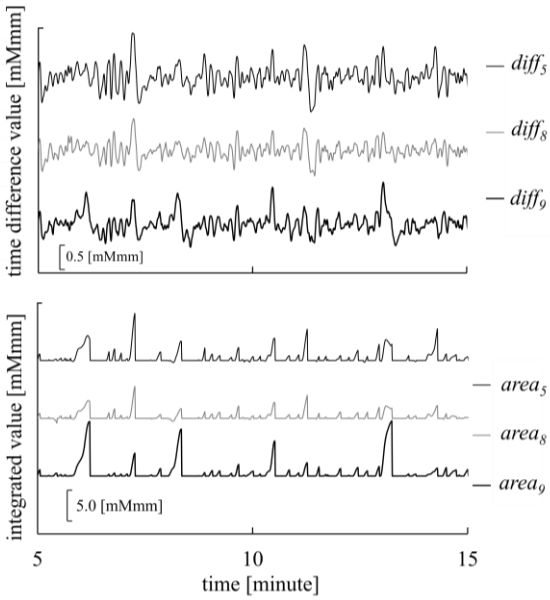

Figure 4. An example of the time difference values for ch5, 8, and 9 (top) and the integrated values calculated from them (bottom).

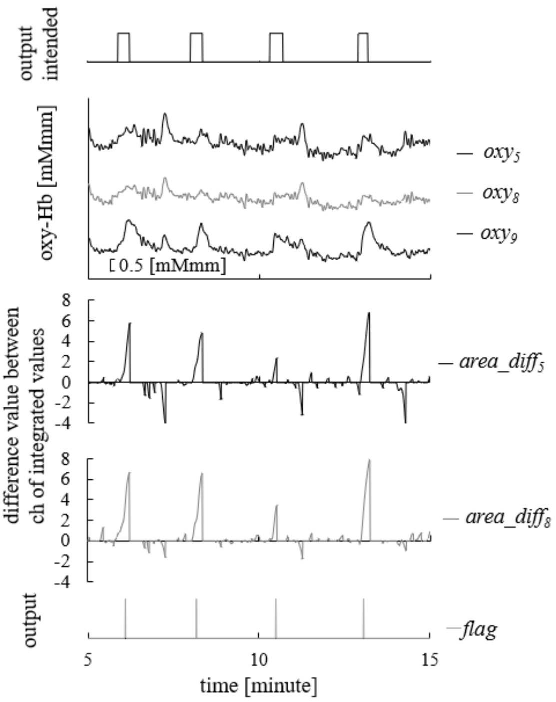

Figure 5. fNIRS waveforms when intending to output and acquired feature values and output results.

C. Determining n and Thresh

In the 13 trials used for acquisition in the experiment, *n* was a variable in the range 1<=*n*<=50 (*n* is an integer), and the threshold *thresh* at that time was a variable in the range 0.1<=*thresh*<=6.0 (*thresh* is an increment of 0.1). Each *n* and *thresh* combination had its BCI output calculated. Then, we calculated the *n* and *thresh* combination with the best output results, then verified the output results at that time. A condition for a successful output was that the subject could have an output within the intended output period, and the number of successful outputs for each trial was recorded. The number of output errors was the number of times there were outputs when not intended and when there was no output when intended. Fig. 6, Fig. 7, and Fig. 8 are examples when *n*=8 and *thresh* is variable. The total number of outputs when not intended and the number of no outputs when intended are shown as output errors. Fig. 8 when *n*=8 and *thresh*=1.7 shows the smallest number of output errors at 8. Fig. 9 shows the relation between *n* and the minimum number of output errors when calculating *thresh* to find the minimum number of output errors for each value *n*. At this time, when calculating *n* to find the minimum number of output errors, we focused on the trials where the number of output errors was 1 or less, i.e., the trials where the total output errors were 13 or less. Then, for the graph in Fig. 9, we made an approximation of the quadratic curve using the least squares method. Fig. 10 shows the results.

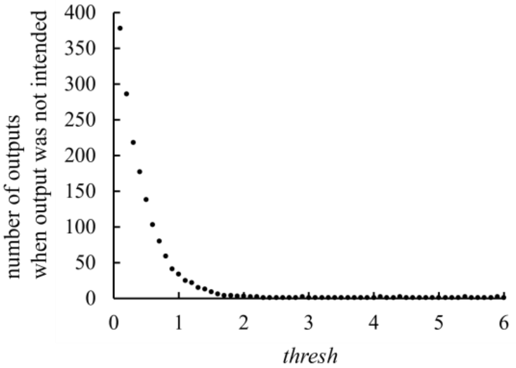

Figure 6. The number of outputs when threshold *thresh* was changed but output was not intended.

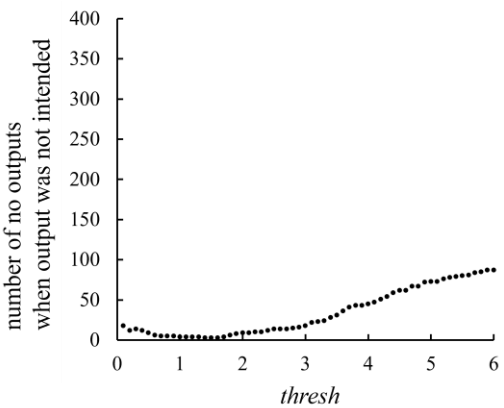

Figure 7. Number of no outputs when threshold *thresh* was changed and output was intended.

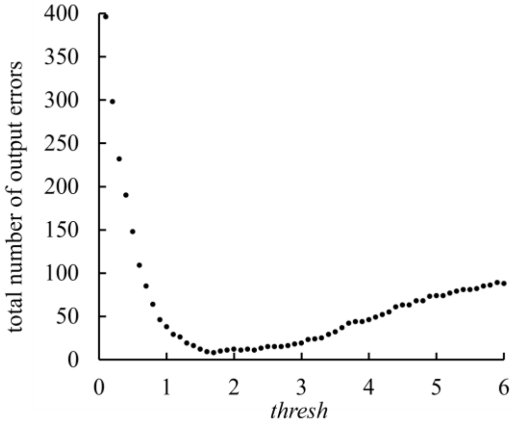

Figure 8. Total number of output errors when the threshold *thresh* was changed.

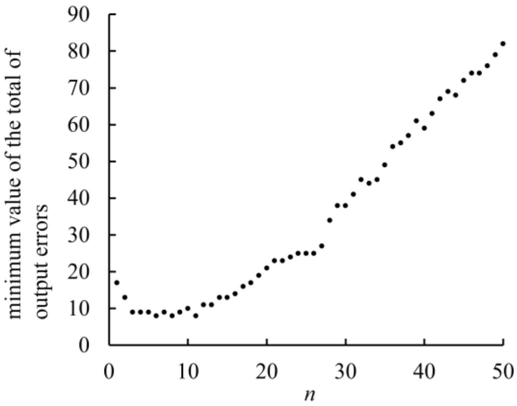

Figure 9. Smallest number of output errors when *n* was changed.

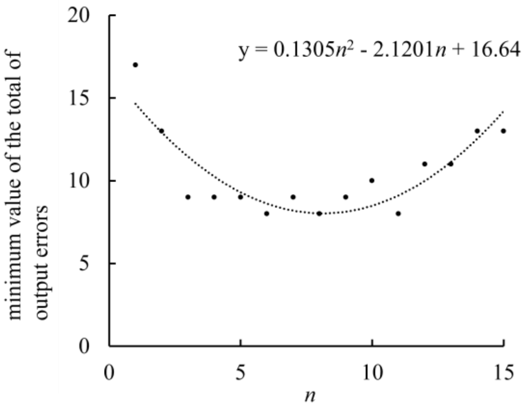

Figure 10. The smallest number of output errors and approximation curve when *n* was changed from 1 to 15.

The minimum value *n* calculated from this approximation curve is *n*=8.122989. Because is an integer, in the 13 trials conducted in our study, we found the best output results when *n*=8 and *thresh*=1.7.

D. BCI Output Using the Determined n and Thresh

Using the *n* and *thresh* values calculated in section *C.*, we calculated the BCI output results for the fNIRS waveforms of the 13 trials we used for analysis. The results were that for the 109 times we intended BCI output, we were successful 104 times; there were four times when there were outputs when none were intended; and there were no outputs four times when outputs were intended. Fig. 11 shows the BCI output results for when output was intended during all 13 trials.

Overall, because we successfully output 104 times when intending to do so 109 times, this indicates that if we can find the optimum *n* and *thresh*, then we should be able to execute highly accurate BCI output. However, as Fig. 11 shows, some trials had three output errors, confirming that some trials had larger numbers of errors. This indicates that it is necessary to adjust the thresholds for each trial in the future.

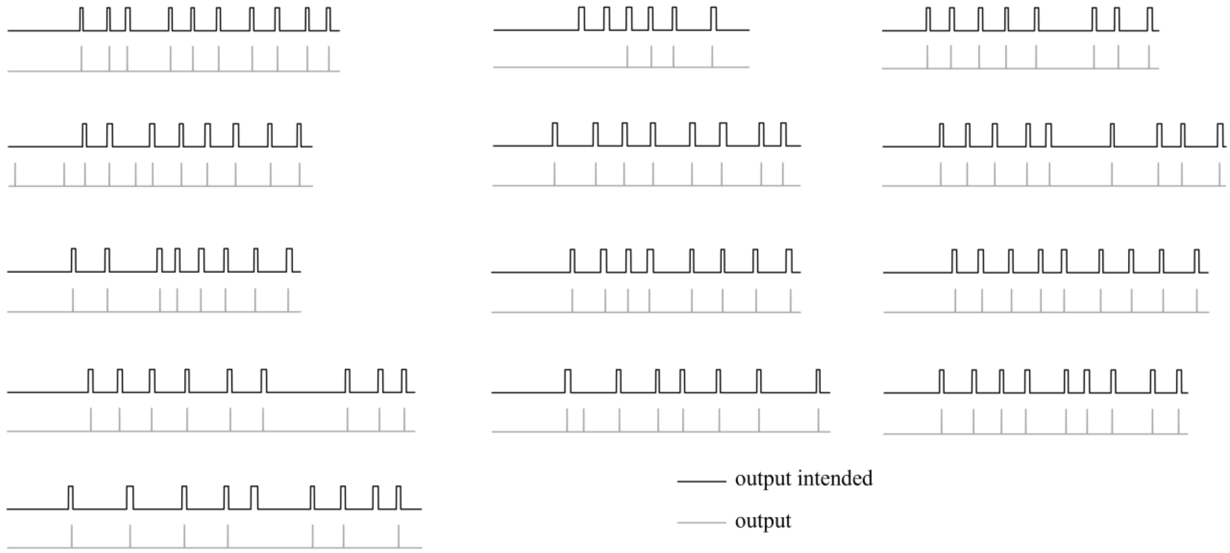

Figure 11. Outputs intended and output results for all 13 trials.

IV. Summary

In this study, we aimed to achieve intentional BCI output by a user by changing the fNIRS waveforms from the central part of the forehead by having the user recollect the experience of eating savory and spicy instant noodle. In other words, we focused on the differences in the amount of change in oxygenated hemoglobin concentration at the upper center of the forehead and the amount of change in oxygenated hemoglobin concentration lower center of the forehead when recollecting the experience of eating led to intentional BCI output. When the amount of change in oxygenated hemoglobin concentration in the lower center of the forehead changes significantly more than the amount of change in oxygenated hemoglobin concentration in the upper center of the forehead, BCI output occurred. The time interval when acquiring the difference value for each probe at set time intervals involves the difference value of the set time interval of the upper probe and the difference value of the set time interval of the bottom probe. By changing the thresholds for the cumulative value of the differences between the probes, we calculated the output results. Our best output result for 109 intended BCI outputs was 104 successful outputs (i.e., a success rate of 94.5%). In comparison, there were four outputs when output was not intended, and four instances of no output when output was intended. We believe this suggests that we can execute highly accurate BCI output by adjusting the time intervals when acquiring the difference value from the set time intervals, and by adjusting the thresholds of the cumulative value of the difference between the probes that measure the difference value of the set time interval for the amount of change in oxygenated hemoglobin concentration lower center of the forehead and that measure the difference value of the set time interval for the amount of change in oxygenated hemoglobin concentration upper center of the forehead. However, it was also confirmed that in certain trials with less than ten outputs, three of those were output errors, so that the number of output errors increased in some trials.

Conflict of Interest

The authors declare no conflicts of interest associated with this manuscript.

Author Contributions

Y. Nakai designed and executed the experiments and wrote the manuscript. M. Nakamura, M. Tomida, and H. Kotani were involved in the data analysis. K. Hoshino is a supervisor and edited the manuscript. All authors critically revised the report, commented on drafts of the manuscript, and approved the final report.

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