Measurement of Spatial and Verbal Working Memory Using N-Back Task by Near-infrared Spectroscopy

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Abstract: In this study, we created two N-back task tasks—a verbal working memory (VWM) task and a spatial working memory (SWM) task. We compared the reaction with numerical working memory (NWM). In the experiment, we utilized NWM, VWM, and SWM 3- and 1-back tasks. We employed near-infrared spectroscopy to measure the response of oxyhemoglobin during the working memory tasks. In the analysis, we used changes in oxyhemoglobin of NWM, VWM, and SWM, activation frequency, and accuracy rate. The results showed that VWM and SWM performed the same measurement as NWM. We obtained no relationship between the correct answer rate and activation of the prefrontal cortex in the 1-back task, but the activity frequency was low. The 3-back task had a lower correct answer rate than 1-back but a higher activation frequency. It means that moderate difficulty can encourage activation.

Keywords: Near-infrared spectroscopy, Working memory, N-back task

1. INTRODUCTION

In recent years, near-infrared spectroscopy (NIRS) has been employed as a clinical tool in medicine and education because of its capability to detect and record human brain functions safely and easily [1]. The frontal lobe is responsible for the highest brain activities in humans. However, it is home to a variety of diseases, such as dementia and mental illness. It is known that working memory (WM) — a frontal-lobe function — decreases with dementia (e.g., Alzheimer’s) [2].

Many attempts have been made to quantify and evaluate frontal-lobe functions. In April 2009, the Ministry of Health, Labor, and Welfare in Japan approved the use of the optical cognitive task of language fluency for cognitive tasks for differential diagnoses of depression symptoms using optical topography testing. NIRS can be employed to harmlessly monitor changes in blood concentrations of oxyhemoglobin, deoxyhemoglobin, and total hemoglobin on the brain surface. It is suitable for measuring changes in blood flow in the frontal lobe and is perfect for assessing N-back tasks.

WM is a biological system that temporarily stores and retrieves information necessary for complex active cognitive tasks, such as language understanding, learning, and inference. This memory type can flexibly cope with various real-time activities and tasks. Besides, it acts as a phonological loop related to verbal information processing. It also provides visuospatial processing to keep track of nonverbalizable information, including visual images. Thus, it can be used to extract information stored in long-term memory and make it usable in addition to holding temporary information [2]. WM depends on the frontal-lobe association area, which distinguishes the types of information retained. These functions together comprise a domain-specific WM module for the human mind [3, 4].

The N-back task test was developed to measure and assess WM functions. For a typical N-back task test, one-digit numbers are presented randomly to measure a subject’s WM. Metrics are obtained by calculating the accurate recollection of a presented number from N-times earlier. Conventional numerical WM (NWM) tasks are suitable to evaluate numerical capability, but they are not suitable for other types of operations, such as verbal and visual.

In the previous research [5], the N-back task using the conventional numbers, which was typically used, was taken as an NWM task, and the two newly created linguistic and spatial N-back tasks were each verbal. The oxyhemoglobin reaction was detected and compared as a WM task and a spatial WM (SWM) task.

Thus, it was not easy to detect and compare the oxyhemoglobin reactions in the NWM, verbal WM (VWM), and SWM tasks in the previous study and compare them with 3- and 1-back tasks. This study investigates the effect of the degree of frontal-lobe activity. We evaluated WM comprehensively by comparing the results of three N-back tasks of different numbers, spaces, and languages.
2. EXPERIMENT OUTLINE

2.1 Experimental Purpose
We performed NIRS measurements for NWM, VWM, and SWM. We examined the frontal-lobe activities of subjects and compared them across the three task types.

2.2 Measuring Instrument
We employed an OEG-16 NIRS device manufactured by Spectratech. It consists of six light-sending and six light-receiving probes (Figure 1), leveraging near-infrared light of two wavelengths (about 770 and 880 nm) to measure the concentrations of oxygenated (i.e., OxyHb) and deoxygenated hemoglobin (i.e., DeoxyHb) 2 to 3 cm below the scalp; their sum is TotalHb. OEG-16 measures these hemoglobin changes using 16 channels. We arranged the light-sending and the light-receiving probes at intervals of 3 cm, and all channels fit within a 15 × 3-cm area. The data-sampling interval is 0.655 s. When mounting the OEG-16, we positioned the center of the holder whose probe was installed at the Fpz midline sagittal plane of the skull according to the International 10–20 system [4]. Specifically, Fpz was set between 7ch and 10ch in the frontal lobe probe.

2.3 Experimental Procedure
We experimented on 14 healthy subjects in their twenties (male:86%, female:14%). Figure 2 shows the experimental procedure. We set the distance between a subjects’ face and the monitor to about 50 cm. There were no moving objects and none with numbers or letters in a subject’s field of view other than test objects. The experimenter stayed directly behind the subjects. The task procedure was fully explained before the experiment. All subjects randomly performed four NWM trials, four SWM trials, and four VWM trials in 3- and 1-back tasks. We established rest conditions beforehand for baseline measurement of blood flow. In the resting state, a white cross was visible on the screen. We conducted the study with the approval of the Kogakuin University ethics review board (approval number: 2019-A-17, Psycho-biological measurement for new interface development).

2.4 N-back Task Test
We displayed nine stimuli corresponding to each task on the experimental screen. We set N to 3 and 1; hence, the tasks were 3- and 1-back tasks. Figure 3 shows the examples of NWM, SWM, and VWM tasks. The subject pressed a button as quickly as possible when the current screen matched the three previous stimuli. We counted the number of correct answers. We displayed each stimulus for 0.5 s with intervals of 1.5 s. We presented a total of 15 stimuli for each trial and included four stimulus matches.

2.5 NWM
We displayed single-digit numbers from one to nine, one at a time. The subject memorized the numbers and pressed the designated button when the number displayed matched the one displayed one or three times earlier. Figure 4 shows an example of the stimulus used for the NWM task.

Figure 1: NIRS channel definition

Figure 2: Experiment flow

Figure 3: Working-memory task (3-back task)

Figure 4: Presentation order of 3-back task NWM tasks
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2.6 SWM

We displayed nine squares, and the subjects remembered the position of the white square. Then, they pressed a designated button when the position of the white square was the same as the position of the one displayed one or three times earlier. Figure 5 shows an example of the stimuli used for the SWM task.

2.7 VWM

For this task, we displayed nine fruit-related words on the screen. The subjects memorized the words. If the word displayed on the screen was the same as the one displayed one or three times earlier, they pressed the designated button. We unified the words into one category to integrate the stimuli. Figure 6 shows an example of the stimuli used for the VWM task.

3. RESULTS

For OxyHb, DeoxyHb, and TotalHb, the change in OxyHb was the most sensitive to regional cerebral blood flow and blood-oxygen-level-dependent (BOLD) imaging signals. We used an OxyHb variation for analysis since it had the highest correlation with BOLD signals [6, 7]. We also calculated the average value of the OxyHb change in the other section. It was baseline corrected, and a 5-point moving average filter was applied [8].

Figure 7 shows the state of brain activity during the 3- and 1-back tasks. The numbers in the figure represent the arrangement of channels. The darker the red color, the greater the amount of brain activation at that site.

In the 3-back task, we measured NWM, SWM, and VWM for 14 subjects a total of 168 times — 56 times for each task. The number of trials in which frontal-lobe activity is observed during NWM, SWM, and VWM are 42, 27, and 31, respectively. Similarly, in the 1-back task, we measured NWM, SWM, and VWM for 14 subjects a total of 168 times — 56 times for each task. The number of trials in which frontal-lobe activity is observed during NWM, SWM, and VWM are 30, 28, and 37, respectively.

We selected the active channel as that whose change in OxyHb showed a positive value 15 s after the start of the task (30 s after the start of the trial), which is the middle of the task sections of NWM, SWM, and VWM. Besides, a trial with one or more activated channels is an activation trial, and a trial with no activated channels is an inactivation trial.
Figure 8 shows the time change from the baseline OxyHb reflecting brain activity in the 3-back task. The horizontal and vertical axes represent time (s) and the amount of change in OxyHb (m mol/L), respectively. The section surrounded by the dotted line indicates where the task is performed.

Figure 9 shows the time change from the baseline OxyHb reflecting brain activity in the 1-back task. The horizontal and vertical axes represent time (s) and the amount of change in OxyHb (m mol/L), respectively. The section surrounded by the dotted line indicates where the task is performed.

Figure 10 shows a comparison of the 3- and 1-back task by integrating the changes in OxyHb during the task sections of NWM, SWM, and VWM. The vertical axis represents the change in OxyHb (m mol/L).

4. DISCUSSION

4.1 3-back Task

Figure 8 shows that the frontal-lobe activity during SWM and VWM increase in the task section, like during NWM. Thus, we deduced that SWM and VWM can be used for WM tasks like NWM. As shown in Figure 10, the change in OxyHb during each task increase in the order of VWM, NWM, and SWM. It suggests that WM can be used more with language tasks than with numerical tasks.

Figure 11 shows the relationship between the activation frequency and the correct answer rate in the 3-back task. The activation frequency represents the number of trials in which activation of the frontal lobe is observed during the four trials of any task of NWM, SWM, and VWM. The horizontal and vertical axes represent the correct answer rate (%) and activation frequency (trials), respectively. The correct answer rates of NWM, SWM, and VWM in the 3-back task were 79%, 76%, and 70%, respectively. We measure the correct answer rate for each trial from the correct button pressed from the time of each stimulus (four matches) to the next, indicating the proportion of subjects who answered correctly during the four matches. Specifically, if a subject answered correctly four times out of the four matches, the correct answer rate would be 100%.

We also observe that in NWM, SWM, and VWM, the activated channels differ depending on the subject. These suggest that there is no difference in the reaction site of the frontal lobe based on the type of information in WM. However, we observe the channels activated by the subjects to be common regardless of the type of task. It indicates that the reaction site of WM in the prefrontal cortex is more affected by the subject’s dominant hemisphere than the type of information.
4.2 1-back Task

Figure 9 shows that the frontal-lobe activity during SWM and VWM increase in the task section, like during NWM. Thus, we obtain that SWM and VWM can be used for WM tasks like NWM.

Figure 12 shows the relationship between the activation frequency and the correct answer rate in the 3-back task. The activation frequency represents the number of trials in which activation of the frontal lobe is observed during the four trials of any task of NWM, SWM, and VWM. The horizontal and vertical axes represent the correct answer rate (%) and activation frequency (trials), respectively. The correct answer rates of NWM, SWM, and VWM in the 1-back task were 98%, 100%, and 85%, respectively.

We measure the correct answer rate for each trial from the correct button pressed from the time of each stimulus (four matches) to the next, indicating the proportion of subjects who answered correctly during the four matches. Specifically, if a subject answered correctly four times out of the four matches, the correct answer rate would be 100%.

Figure 8 shows no significant difference between the correct answer rate of trials in which activation is observed in the frontal lobe and those in which activation is not observed in the frontal lobe since the correct answer rate is almost 100%. Although the correct answer rate is 100%, there are many trials in which activation is not observed in the frontal lobe. This is because the load of the 1-back task is so small that the subject did not affect the activation of the frontal lobe. We also observe that the activated channels differ depending on the subject in NWM, SWM, and VWM. These suggest that there is no difference in the reaction site of the frontal lobe depending on the type of information in the 1-back task in WM. Moreover, we observe that the prefrontal cortex responds extensively to the activated channels of the subjects regardless of the type of task. Thus, it suggests that the reaction of WM in the prefrontal cortex in the 1-back task is not partial but whole.

As shown in Figure 12, the amount of change in OxyHb during each task increases in the order of SWM, VWM, NWM. It suggests that in the 1-back task, WM may be employed more during tasks using spatial information than those using numerical information.

4.3 Comparison of 3- and 1-back Tasks

As shown in Figure 7, we observe that the activated trials are not localized reactions based on the activated sites in the frontal lobe; however, many trials in which the entire prefrontal cortex responds. We expected the brain activity in the prefrontal cortex to increase proportionally as the correct answer rate approaches 100%. However, we observe that the correct response rate and prefrontal cortex brain activity are not necessarily proportional. There is a neural resource as a concept for a detailed explanation. According to this, if the task with a low load is processed using neural resources and brain activation is seen as the load increases, the capacity of neural resources is exceeded in the task with a high load. Thus, it is said that the ability to perform and the activation of the brain decline [9].

In this study, the 3-back task is a high load task that requires three times as much WM as the correct answer compared to the 1-back task. Although it is 100% at the 3-back task in the trial where the brain activation is not observed in the prefrontal cortex, the task load exceeds the capacity of the subject’s neural resources. It may be because the brain activation in the anterior cortex cannot be measured. In addition, in this experiment, there is a possibility that the amount of brain activation has decreased that it cannot be measured due to repeated work despite taking sufficient breaks between trials.

Comparing the reaction sites of the 3- and 1-back tasks, we obtain no regularity in both reactions, and they reacted widely. Helton et al. reported that NIRS measurements were performed on the frontal lobe during task execution in response to the target stimulus that appeared on the screen with visual interference. They also reported that the left-right superiority of brain activation differed depending on the degree of difficulty. It has been shown that in a task requiring continuous attention with a low difficulty level, the right side is activated [10]. The N-back task in this experiment is a task that requires continuous attention; however, we observed no such characteristics. In the reaction site of VWM, both 3- and 1-back tasks are located on the left side of the channel, where the amount of change in OxyHb is highest. This is because language

Figure 12: Activation frequency and correct answer rate (1-back task)
memory is said to be functionally localized on the left side [11].

As shown in Figure 10, the magnitude of change in OxyHb during each task is different between 3- and 1-back tasks. For SWM, the amount of change in OxyHb is lower in the 3-back task compared with NWM and VWM but reversed in the 1-back task. It may be because NWM and VWM are common in language processing, but they are problems with non-language information.

Comparing the brain activation amounts of the 3- and 1-back tasks, the 3-back task is larger, as shown in Figure 10. NWM, SWM, and VWM tend to increase brain activation by increasing the difficulty level. Thus, we can infer that SWM and VWM can be used as a WM task like NWM.

The data on brain activation reactivity vary widely. Besides, the results’ tendency may change as the number of data changes. Thus, indicating a limit to narrowing down to one conclusion. In the future, it is necessary to increase the number of data, and further study is needed.

5. CONCLUSION

In this study, we created two N-back task tasks: a verbal working memory (VWM) task and spatial working memory (SWM) task. Responses were compared to numerical working memory (NWM). The experiments used NWM, VWM, and SWM 3- and 1-back tasks. We adopted the near-infrared spectroscopy to measure the response of oxyhemoglobin during the working memory task. In the analysis, we utilized NWM, VWM, and SWM activation channels, the number of trials observed for activation, and the accuracy rate.

As a result, both VWM and SWM were able to perform the same measurements as NWM. In addition, the correct answer rate for each 3-back task was NWM 79%, SWM 76%, and VWM 70%. The correct answer rate for each 1-back task was NWM 100%, SWM 98%, and VWM 85%. Comparing the activity frequencies of each, the 3-back task with the correct answer rate was higher than the 1-back task with the correct answer rate of almost 100%. Thus, a suitable degree of difficulty may encourage activation. In the future, it is necessary to increase the number of subjects and study the spatial area of WM.

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