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Activation of the Anterior Prefrontal Cortex by Abacus Activity in Children: A Case Study on the Effect of Moderate Load Training on Working Memory

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Abstract

Much attention has been paid to the enhancement of working memory, which can improve children's lives. Part of the value of working memory training is that it activates the prefrontal cortex. Therefore, it is important to determine the parts of the prefrontal cortex that are activated by working memory training. While there is much evidence that mental abacus effectively trains working memory, few studies have assessed whether the abacus (*Soroban*) in Japan should be considered an effective training approach for working memory and if it activates the prefrontal cortex. Therefore, in this case study, a 16-channel functional near-infrared spectroscopy device (OEG-16H, Spectratech, Japan) was used to compare brain activation during the abacus task using the Wechsler Intelligence Scale for Children Working Memory Index tasks (i.e., digit span (forward), digit span (backward), letter–number sequencing, and picture span tasks). First-grade boys and fifth-grade girls participated in this study. The results revealed that the anterior part of the prefrontal cortex was specifically activated by the abacus task. These findings support the possibility that the abacus activity is an effective training approach for working memory.

Keywords: working memory, abacus, prefrontal cortex, fNIRS, training, case study

1. Introduction

Working memory, which is a temporary storage system under attentional control, is believed to render humans capable of complex thinking (Baddeley, 2007). Although there are several models of working memory, Baddeley's model, which is termed the multicomponent working memory model, is the most supported (Chai, Abd Hamid, & Abdullah, 2018). This model consists of a four-element structure, including a central executive system and three information-retention systems, namely, a visuospatial sketchpad, episodic buffer, and phonological loop (Baddeley, 2012). Working memory plays a crucial role in many cognitive processes, and it is considered the conductor of the brain (Alloway & Alloway, 2014). Examples of these diverse processes include prioritizing information, focusing on what is important, thinking quickly, taking smart risks, learning smoothly, making personal decisions, adapting to new environments, staying motivated, achieving long-term goals, staying positive in dire situations, following one's morals, and being a good athlete (Alloway & Alloway, 2014). Moreover, working memory skills are closely related to learning (Gathercole & Alloway, 2008). Working memory relates to prefrontal cortex activation (Dehaene, 2020; Mushiake, 2019), which shows stronger activation when a memory task is moderately difficult (Watanabe, 2008).

Working memory is one of the most important cognitive abilities for successful behavior in and out of school (Alloway & Alloway, 2014). Therefore, it is desirable to progressively develop working memory starting in early childhood. However, at present, there is no clear answer as to how best to train one's working memory (Gathercole & Alloway, 2008). However, recent training studies of working memory have shown that although working memory capacity is unlikely to change, the effects of training are generalized, and evidence has been collected on the effects of the far transfer of the training. (Alloway & Alloway, 2014). As an approach to working memory training in Japan, it is important to consider the abacus, because in this country the abacus is treated as a regular tool in schools; moreover, a large body of evidence has been collected on the mental abacus related to the abacus (Wang, 2020). For example, long-term mental abacus training improves arithmetic ability and potentially has a positive effect on visuospatial working memory (Wang, et al., 2019). The mental abacus has also been demonstrated to activate neural resources concerning working memory (Dong, et al., 2016) and to influence higher-order mathematical abilities and modulate the relationships between switch cost and mathematical abilities (Wang et al., 2015). Furthermore, there is preliminary evidence of the abacus activity's effects on the brain based on the use of a two-channel functional near-infrared spectroscopy (fNIRS) device (Watanabe, 2021). Given these findings, working memory training using an abacus may be valuable during childhood.

In this study, I aimed to investigate whether abacus activity activates the anterior prefrontal cortex by providing moderate load training for working memory. This study is presented as a case study, because a case study can derive new hypotheses and possibilities (George & Bennett, 2005).

This study validated this relationship between abacus training and working memory based on the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH) (Reuter-Lorenz & Cappell, 2008). To do so, their brain activation was assessed while working on the Wechsler Working Memory Index (WMI) tasks (digit span (forward), digit span (backward), letter–number sequencing, and picture span tasks) and abacus task. Specifically, this case study measures brain activity — specifically prefrontal cortex activity — in children using a 16-channel fNIRS device (OEG-16H, Spectratech, Japan).

2. Method

2.1 Participants

Two children participated in this study: a 6-year-old boy (a right-handed first grader in a public elementary school) and a 10-year-old girl (a right-handed fifth grader in a public elementary school).

2.2 Ethics

This study was reviewed and approved by the Kwansei Gakuin University Committee for Regulations for Behavioral Research with Human Participants (Approval Number: 2020-06; approval date: June 12, 2020). The participants' legal guardians or next of kin provided written informed consent to participate in this study.

2.3 fNIRS Measurement and Protocol

Brain activity was measured using a 16-channel fNIRS device (OEG-16H, Spectratech) while performing the two tasks, namely the Wechsler Intelligence Scale for Children (WISC) WMI tasks (digit span (forward), digit span (backward), letter–number sequencing, and picture span) and the abacus task. Prefrontal cortex activation was assessed using a 16-channel fNIRS device.

Brain activity was measured during the task execution. Data were excluded when abnormal results were obtained or when data collection was incomplete. The change in oxyhemoglobin concentration (Ox-Hb, in mMmm) was calculated. Ox-Hb at the 16 channels in the prefrontal cortex was measured every 0.65536 s.

2.4 Tasks

Each task was performed once daily for 10 days in August 2022, for 10 times. Participants relaxed for a few minutes before starting the tasks and between each task. The task durations were as follows: 3 min of active task time and 1 min of rest time for first graders, and 5 min of active task time and 1 min of rest time for fifth graders. The order of the tasks was randomized.

The individual tasks are described in detail below. The tasks were originally terminated by a stop condition, albeit in a time-limited manner. The tasks were resumed when the stop condition was achieved.

2.4.1 Digit Span (Forward) Task

The duration of the test was 3 or 5 min. The inspector read out a sequence of 2–10 numbers (e.g., 2, 6, 8, 5) and the child answered accordingly (e.g., 2, 6, 8, 5). Generally, the task started with two digits followed by two sequences with the same number of digits, and the numbers in the sequence then increased. If the child could not answer, the task was restarted using a reduced number of digits.

2.4.2 Digit Span (Backward) Task

The duration of the test was 5 or 3 min. The inspector read out a sequence of 2–8 numbers (e.g., 2, 6, 8, 5) and the child answered in the reverse order (e.g., 5, 8, 6, 2). As a rule, there were 2–4 number sequences with the same number of digits, starting with two digits, followed by an increase in the number of digits in the sequence. If the child could not answer, the task was restarted with a reduced number of digits.

2.4.3 Letter–Number Sequencing Task

The duration of the test was 3 or 5 min. The inspector read out a number string of 2–7 *hiragana letters* combined with numbers (e.g., 4, *o,* 1, *a*), and the child answered by sorting the numbers in ascending order and the *hiragana* in Japanese syllabic order (e.g., 1, 4, *a*, *o*). The task started using two letters (one hiragana letter and one number). There were six number sequences consisting of two letters (hiragana letter and number), followed by nine number sequences consisting of three letters; six number sequences consisting of four letters; and three number sequences of five, six, and seven letters each. If the child was not able to answer, the task was restarted with a reduced number of letters.

2.4.4 Picture Span Task

The duration of the test was 3 or 5 min. The inspector presented cards with 2–8 pictures in a horizontal row for 5 s. The children were instructed to memorize the pictures in order, starting with the one on the left. The inspector then presented the next card with 2–6 additional pictures. The child then pointed to the pictures they had memorized in order.

2.4.5 Abacus Task

In the abacus task, an abacus, which is a tool used for performing calculations, was employed. For performing calculations, the beads of the abacus are moved and their position is used to represent the number. In this case, for the abacus task, the first grader calculated 10 four-digit numbers, including addition and subtraction per question (e.g., 6830 + 9542 – 3601 – 4792 + 5187 + 6409 + 7325 – 8073 – 1968 + 5213), and he calculated as many questions as he could within the time limit. The fifth grader calculated 10 five-digit numbers, including addition and subtraction per question (e.g., 32850 + 61472 + 27139 + 43068 − 56943 − 10789 + 84605 – 45032 − 21897 + 79517), and she calculated many questions as she could within the time limit.

2.5 Statistical Analysis

Data collection, analysis, and discharge were performed using OEG16.exe software (Spectratech). For the fNIRS data, the collected data were baseline corrected, hemodynamic separation was applied, data analysis was performed as brain function components, and the data were outputted as Excel (Microsoft, USA) data. Excel was used to calculate the mean values at each measurement time and create a histogram of the task time. A *t*-test using SPSS software (IBM, USA) was used to compare the mean values of the abacus task and those of other tasks for each channel. Cohen's d-effect sizes were calculated using SPSS software (IBM).

3. Results

The measured points for each channel are shown in Figure 1. Histograms of the average ox-Hb value at each measurement time for each task are shown in Figures 2 and 3.

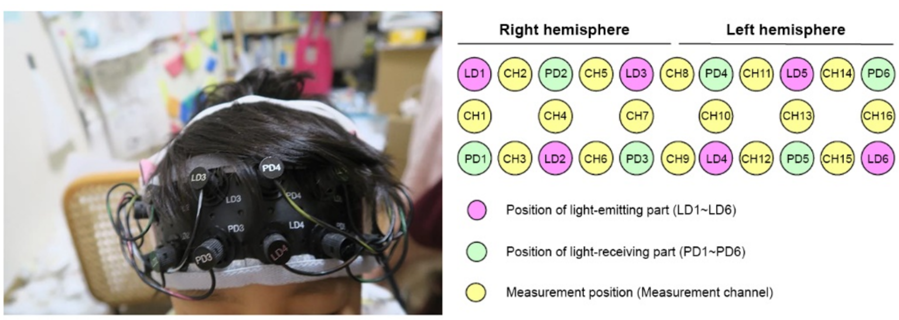

Figure 1. Measurement points of each channel (the image on the left depicts a first-grade participant, while the image on the right is from Spectratech, Inc. (2020), p. 6)

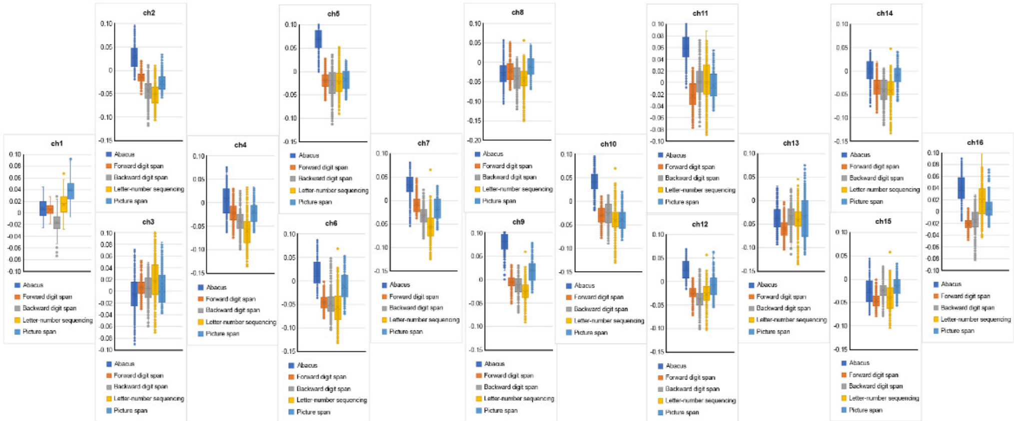

Figure 2. Histograms of the average ox-Hb value at each measurement time for each channel for each task in the fifth-grade participant

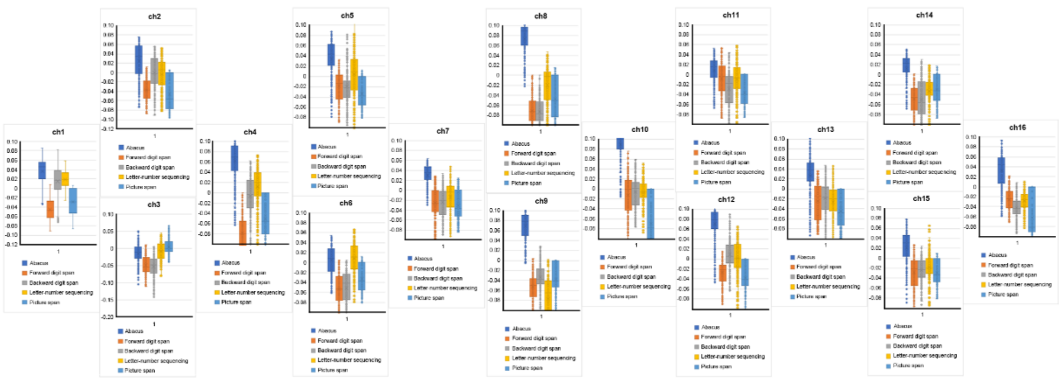

Figure 3. Histograms of the average ox-Hb value at each measurement time for each channel for each task in the first-grade participant

Figure 2 depicts the results for the fifth grader. The activation of ox-Hb in ch 2, 4, 5, 6, 7, 9, 10, 11, 12, and 16 was considerably or slightly higher during the abacus task than the WMI tasks. Notably, seven of the eight channels in ch 5–ch 12 in the anterior frontal area were more activated during the abacus task than the other tasks. In ch 1, activation on the picture span task was higher than that observed for the other tasks. In ch 3, 8, 13, and 15, the same level of performance was detected for each task. Lastly, in ch 14, the abacus task and picture span task tended to be slightly superior.

Figure 3 depicts the results for the first grader. The activation of ox-Hb in ch 1, 2, 4, 5, 7, 8, 9, 10, 12, 13, 14, 15, and 16 was fairly or somewhat higher during the abacus task than the WMI tasks. Six of the eight channels in ch 5–ch 12 in the frontal-frontal area were more activated during the abacus task than the other tasks. In ch 3, performance on the picture span task was slightly better than that for the other tasks; in contrast, in ch 6, the performances on the abacus task and letter–number sequencing task were slightly better, and ch 11 exhibited a similar level of activation.

A common trend for both children is that the abacus task has a greater number of active channels than the other tasks. It also tends to be more active in more anterior areas.

Table 1 shows the p-values and Cohen's d-effect size for channels 7–10, as determined using a *t*-test. The values relate to the difference between the mean of the abacus task and the mean of the other tasks. A positive significant difference was observed for all comparisons with the abacus task, except for the forward digit span and picture span task for ch8 in the 10-year-old girl. The effect sizes were >1 for all channels except ch 8 in the 10-year-old girl.

Table 1. Results of the comparison of the mean activation values for channels 7 to 10 between the abacus task and other tasks

			10-year-old girl		6-year-old boy	
Ch			P-value	Cohen's d	P-value	Cohen's d
7	Ab	Fw	<.001 **	1.03	<.001 **	1.46
		Bw	<.001 **	1.60	<.001 **	2.10
		LNS	<.001 **	2.26	<.001 **	1.09
		PS	<.001 **	1.49	<.001 **	1.46
8	Ab	Fw	<.001 **	−0.17	<.001 **	2.43
		Bw	<.001 **	0.28	<.001 **	3.05
		LNS	<.001 **	0.37	<.001 **	1.53
		PS	<.001 **	−0.39	<.001 **	1.93
9	Ab	Fw	<.001 **	3.51	<.001 **	3.26
		Bw	<.001 **	3.29	<.001 **	3.25
		LNS	<.001 **	3.49	<.001 **	2.68
		PS	<.001 **	2.34	<.001 **	2.41
10	Ab	Fw	<.001 **	2.01	<.001 **	1.56
		Bw	<.001 **	2.06	<.001 **	2.11
		LNS	<.001 **	1.96	<.001 **	1.91
		PS	<.001 **	2.35	<.001 **	2.45

Ab: Abacus task, Fw: Forward digit span, Bw: Backward digit span,

LNS: Letter–number sequencing, PS: Picture span

Note: †$p < 0.1$, *$p < 0.05$, and **$p < 0.01$.

4. Discussion

4.1 Is the Abacus an Effective Working Memory Training Tool?

For each of the WMI tasks compared here, its involvement in working memory was as follows: The forward digit span task is a simple span task, whereas the backward digit span task and letter–number sequencing task are complex span tasks (Conway, Macnamara, & Engel de Abreu, 2013). The forward digit span task involves the phonological loop; the backward digit span task involves the phonological loop, central executive, and visuospatial sketchpad (St Clair-Thompson & Allen, 2013); and the letter–number sequencing task primarily involves the phonological loop and central executive as well as the visuospatial sketchpad (Crowe, 2000). The picture span task is thought to involve all three components (The Japanese WISC-IV Publication Committee, 2022). Overall, the WMI tasks are extensively involved in each function of working memory. Notably, the experimental results clearly showed that activation tended to be stronger during the abacus task than during the WMI tasks. Therefore, based on CRUNCH, the abacus task appears to be an effective method for training working memory.

4.2 What is Activated During a Working Memory Task?

Working memory is related to the prefrontal cortex (Dehaene, 2020; Mushiake, 2019). This brain region can be broadly separated into the dorsolateral prefrontal cortex, medial prefrontal cortex, and orbitofrontal cortex (Shimada, 2017). The anterior part (anteriorly, including Brodmann area 10) is said to be involved in higher hierarchical processing compared with the posterior part (Mushiake, 2019; Koechlin & Hyafil, 2007). Broadmann area 10 has also been implicated in metacognition (Burgess & Wu, 2013). The results of the present study revealed that the central part is particularly activated during the abacus task; i.e., the more sophisticated execution system is affected. During the abacus task, the participant must simultaneously grasp the numbers with their eyes, move the beads with their fingers, and perform calculations with their mind. Based on these facts, it can be inferred that the high-level executive system is activated by the abacus task.

4.3 Is There Any Other Value in Abacus Training?

While working memory training may be of value, the size and length of the effect will vary from person to person. Thus, the question remains as to whether the abacus has any effect on working memory. Abacus training is useful, for example, in problem-solving. Because working memory has a limited capacity, it is important to avoid overloading it when solving problems (Willingham, 2021). In this respect, being able to use the abacus affects easing the computational load, which is expected to have an indirect positive effect on working memory. Thus, abacus training is expected to “kill two birds with one stone” regarding working memory.

4.4 Ripple Effects

Although the abacus has been used for a long time in Japan, it has recently fallen out of use because of the spread of personal computers and calculators. However, the abacus is still regularly used as a tool in schools and can be easily and inexpensively obtained at 100-yen stores. These findings of the value of the abacus for working memory training contribute to research in the fields of neuroscience and cognitive psychology as well as to the practical areas of school and home education, offering important implications.

4.5 Limitations

The limitations of this study are as follows. First, individual differences in brain activity measurements are an unavoidable issue in this context. However, even if generalizations are made, individual differences will remain; trends for specific individuals can only be determined based on the measurement results. Although this study included only two subjects, they were distinct: one was a lower elementary school student and the other was an upper elementary school student.

4.6 Conclusion

In this case study, a 16-channel fNIRS device (OEG-16H, Spectratech) was used to compare brain activation during the abacus task and Wechsler Intelligence Scale for Children WMI tasks (digit span (forward), digit span (backward), letter–number sequencing, and picture span tasks). One first-grade boy and one fifth-grade girl were the subjects of this study. The results revealed that the anterior part of the prefrontal cortex in particular was activated by the abacus task. These findings suggested the characteristics of the activation afforded by the abacus activity and the possibility that this is an effective training approach.

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