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Mental abacus training affects high-level executive functions: Comparison of activation of the frontal pole

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ABSTRACT

The role of executive function training in supporting child development has been increasingly studied. Executive function is largely related to the prefrontal cortex. The anterior portion of the prefrontal cortex, which is area 10 on the Brodmann map, is essential for the emergence of higher-order executive functions. Accumulating evidence indicates that mental abacus training, which is closely related to mathematics education, activates the prefrontal cortex. Based on these findings, it can be hypothesized that the mental abacus is valuable for training more advanced functions. Therefore, this study analyzed the activation of children's brains with a focus on the frontal pole (Brodmann area 10). The results illustrated that mental abacus task more strongly activated the brain than piano task, the marshmallow test, or letter–number sequencing tasks. Thus, it was suggested that the mental abacus is valuable for training higher-level executive functions (i.e., frontal pole).

Keywords: mental abacus, frontal pole, functional near-infrared spectroscopy, executive function

INTRODUCTION

Currently, enhancing children's well-being is an important issue worldwide (OECD, 2019). World Health Organization (WHO) defines well-being as "a positive state experienced by individuals and societies. Similar to health, it is a resource for daily life and is determined by social, economic and environmental conditions" (WHO, 2021, p. 10). Socio-emotional skills (non-cognitive skills) influence the well-being of an individual (Ikesako & Miyamoto, 2015). The non-cognitive skills underscores the significance of nurturing it during childhood, as it can play a critical role in determining future success (Crehan, 2018; Heckman, 2013; OECD, 2015; Watanabe, 2019).

Non-cognitive skills include self-perceptions, motivation, perseverance, self-control, metacognitive strategies, social competencies, resilience and coping, and creativity (Gutman & Schoon, 2013). Executive function is associated with non-cognitive skills, in particular, "ability to control oneself to achieve goals" is related (Moriguchi, 2019). Evaluation of this executive function is quite challenging. However, with advances in science and technology, physiological evaluation has now become possible. For example, non-invasive measures of brain function can be used to evaluate (Fiske & Holmboe, 2019; Goddings et al., 2021; Moriguchi & Hiraki, 2013; Yasumura et al., 2014). And the relationship between the prefrontal cortex and executive function has been evaluated with non-invasive brain function measures (Friedman & Robbins, 2022; Menon & D'Esposito, 2022; Moriguchi, 2022; Panikratova et al., 2020). Magnetic resonance imaging (MRI) and near infra-red spectoroscopy (NIRS) are other techniques for non-invasive brain function measurement. Although the measurements are easy to obtain neurophysiological evidence, many devices are difficult to set up and are burdensome to the patient. Functional near-infrared spectroscopy (fNIRS) is inexpensive, and its use reduces the subject's behavioral restrictions during measurement (Watanabe, 2021a, 2021b, 2023). Hence, while considering the enhancement of children's well-being, it is worthwhile to examine the support of executive functions and to employ neuroscience in doing so. Therefore, in this study, I would like to explore an approach to brain science-based executive function support.

There is growing interest in executive function training for supporting child development. This is because the level of executive function determines a child's later academic, economic, and health status, and it is susceptible to support and environmental influences (Moriguchi, 2019). Executive functioning is described as "goal-oriented, thought, action, and emotional control" (Moriguchi, 2015). Although there is no unified model of execution function, two models are commonly used: Baddeley et al.'s model of a central execution system with working memory (Baddeley, 2007), which is a single model, and Miyake et al.'s (2000) model, which divides working memory into multiple components, namely "inhibition, shifting, and updating" (Moriguchi, 2012). However, in both models, executive functions are closely linked to the prefrontal cortex (Duncan, 2001; Kane & Engle, 2002; Miller & Cohen, 2001; Moriguchi, 2012; Watanabe, 2021b, 2022). The prefrontal cortex is divided into the dorsolateral prefrontal, medial prefrontal, and orbitofrontal cortices (Mushiake, 2019). Advanced executive functions are said to involve more anterior areas (Jeon & Friederici, 2015; Mushiake, 2019), namely the frontal pole, representing area 10 on the Brodmann map.

Although many unclear points remain (Ramnani & Owen, 2004), it has been pointed out that the frontal pole may be essential for the emergence of higher-order executive functions. For example, it is reported to be related to “the task set” (Sakai, 2008), “the processing of cognitive branching based on reward expectations with no supervisory optimization is the core function” (Koechlin & Hyafil, 2007), “gateway hypothesis (high possibility of supporting core functions of cognition)” (Burgess et al., 2007), and “metacognition” (Miyamoto et al., 2018). Executive function is noted to have both HOT and COOL aspects (Zelazo & Carlson, 2012). On COOL side, WISC-V WMI task measures working memory. The letter-number sequencing task is associated with executive function (Wechsler, 2022). Conversely, the marshmallow test assesses the HOT aspect (Moriguchi, 2019). For these tasks, a relationship with the prefrontal cortex has been identified concerning the letter-number sequencing task (Haut et al., 2000). A relationship with the prefrontal cortex has also been noted for the marshmallow test (Mischel, 2014). Meanwhile, “piano” and “mental abacus” are sometimes mentioned as familiar training aspects that support executive function (Bugos et al., 2007; Wang et al., 2017). The marshmallow test itself has also been described as a training task (Watanabe, 2022). In this study, the mental abacus refers to calculations that are performed by imagining the abacus in one’s mind (Frank & Barner, 2012). In other words, it can be said that the mental abacus is based on the actual abacus. In Japan, although the use of the abacus has been drastically decreasing, its use is formally taught in schools (Ministry of Education, Culture, Sports, Science, and Technology, 2017). Therefore, it is worthwhile to examine the utility of mental abacus training for mathematics education. Although previous studies investigated the effects of mental abacus training on the prefrontal cortex (Tanida et al., 2004), little research has examined its effects on the frontal pole. However, mental abacus training involves special brain activity because it requires a similarly high degree of ability to perform as regular abacus training (Hatano & Osawa, 1983). Therefore, it can be hypothesized that the frontal pole is activated.

Therefore, this study tested the hypothesis that mental abacus training affects higher executive functions (frontal pole); i.e., it has training value. Specifically, the hypothesis was tested by comparing the effects of the letter-number sequencing task, marshmallow test, and piano task to those of mental abacus task. For hypothesis testing, brain activation was investigated using a 16-channel fNIRS device. There have been various studies in recent years that have examined brain activation of the prefrontal cortex using 16-channel fNIRS (Bigliassi et al., 2015; Ozawa et al., 2014; Rodrigo et al., 2016; Takeuchi et al., 2017, 2019; Yeung et al., 2021).Case studies were employed because they are effective for identifying new issues (George & Bennett, 2005).

MATERIALS AND METHODS

Targets

One boy and one girl attending a local public elementary school were targeted. The girl was a right-handed fifth grader (10 years old). The boy was a right-handed first grader (6 years old). The girl has been attending a soroban juku since she was 6 years old and a piano juku since she was 4 years old. The boy has been attending a soroban juku since he was 5 years old and a piano juku since he was 6 years old.

Brain Activity Measurement

Brain activity was measured ten times in August 2022. As a rule, each task was performed for the same amount of time in each session with a basic 1-min break between tasks. In principle, the order of implementation was random. For the 10-year-old participant, the letter–number sequencing, piano, and mental abacus tasks were conducted for 5 min, and the marshmallow test was conducted for 15 min. The 6-year-old participant was given 3 min to complete the letter-number sequencing, piano, and mental abacus tasks and 15 min to finish the marshmallow test. Oxyhemoglobin (Ox-Hb) concentration changes in cerebral blood flow in the prefrontal cortex were measured during each task. The measurement points are presented in **Figure 1**.

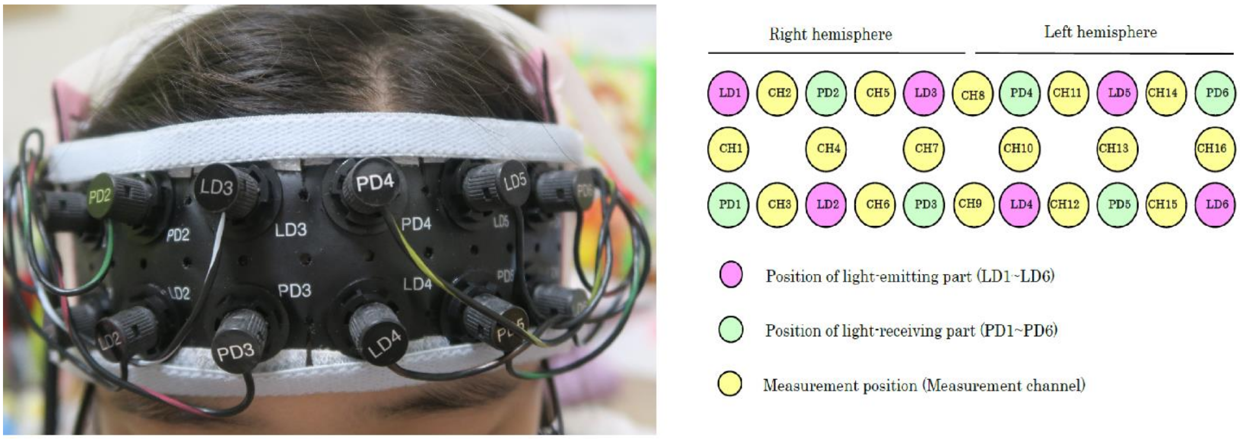

Figure 1. Measurement points of each channel (left photo presents the measurement points for the 6-year-old boy, and the right image was obtained from Spectratech, 2020) (LD: Light-emitting diode, PD: Photodiode & CH: Channel) (Source: Left Figure: Author’s own elaboration; Right Figure: Spectratech, 2020)

Task/Protocol

Letter-number sequencing task

WISC-V implementation and scoring manual (Wechsler, 2021) was followed. However, the abort condition was not employed, and the task was repeated within the time limit. Specifically, a sequence of numbers and hiragana was said by the investigator at first. The subject first said the numbers in ascending order and then the hiragana in syllabic order. For example, [3-*a*-1-*o*] would be read as [1-3-*a*-*o*]. The test initially consisted of two pieces: one number and one hiragana. Then, the number of columns was incrementally increased by one. If the same number of rows cannot be memorized consecutively, the number of rows was decreased again, and the test was repeated.

Marshmallow test

In principle, the previously reported procedure for conducting the marshmallow test was followed (Mischel, 2014). In the test, a marshmallow (or favorite snack) was placed on a plate on the table. The target was then told that if he or she could resist eating for 15 min, then he or she would be able to receive double the snack; if not, he or she would not be able to receive extra snacks. The subject was allowed to stop the test by ringing a bell.

Piano task

In this task, the subject played a piece of sheet music that he or she had been practicing on the piano juku.

Mental abacus task

The girl solved a problem of adding five three-digit numbers, and the boy solved a problem of adding five numbers with two one-digit and three two-digit numbers. They solved as many problems as possible within the time limit.

Calculation

Brain measurements were performed using an OEG-16H 16-channel fNIRS device (Spectratech, Japan). Ox-Hb levels were measured every 0.655359 s for 16 channels in the prefrontal cortex. Measurements were collected, analyzed, and discharged using OEG16 software (Spectratech, Japan) supplied with the instrument. The collected data were baseline-corrected, hemodynamic separation was applied, and the data were analyzed as brain function components. The data were outputted to Excel files.

Data were omitted when clearly abnormal results were obtained or when data collection was impossible. For the marshmallow test, the values for the first 5 min after the start of the test were adopted. The average value of each measurement time was calculated in Excel. Box-and-whisker plots were created for each channel for each task. Trends in the difference between each mean, the second quartile, and the interquartile range were examined. In addition, t-tests for determining the difference between the means of the mental abacus task and each of the other tasks were conducted for each channel, and the effect size of Cohen’s d was calculated using SPSS.

RESULTS

Figure 2 presents the Ox-Hb concentration in each channel for each task for the 10-year-old girl. In ch7, ch8, ch9, ch10, ch12, ch13 and ch16, the Ox-Hb concentration for the mental abacus task was higher than those for the other tasks. In ch4 and ch6, the Ox-Hb concentrations for mental abacus and piano tasks were higher than those for the other tasks.

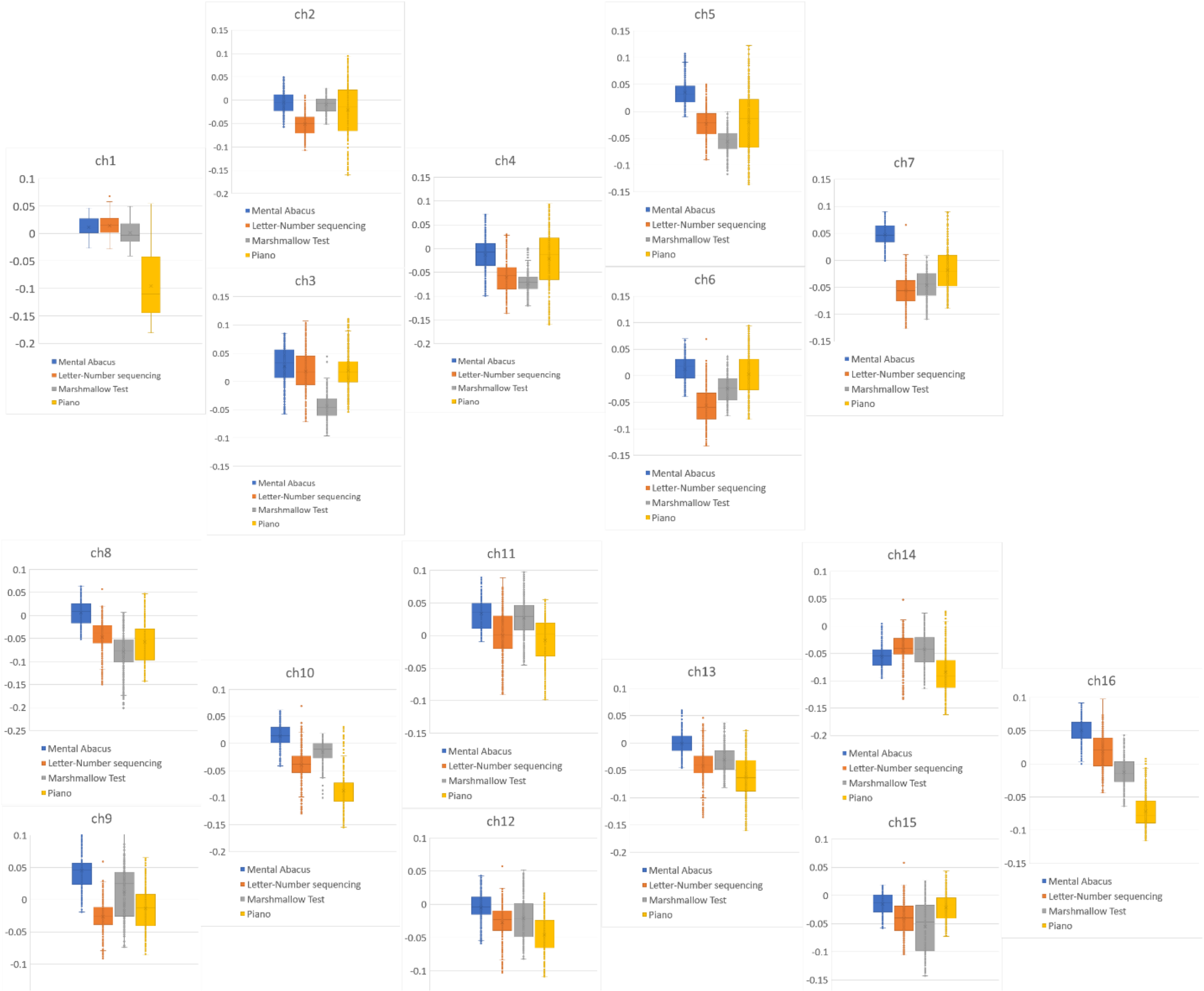

Figure 2. The result for the 10-year-old girl (Source: Author's own elaboration)

Figure 3 presents the Ox-Hb concentration in each channel for each task for the 6-year-old boy. In ch1, ch4, ch5, ch7, ch8, ch9, ch10, ch12, and ch14, the Ox-Hb concentration was higher for the mental abacus task that for the other tasks. In ch2, the Ox-Hb concentrations for the mental abacus and piano tasks were higher than those for the other tasks. In ch3, ch15 and ch16, the Ox-Hb concentration was higher for the piano task than for the other tasks.

The common denominator of both is the Ox-Hb concentration was numerically higher for the mental abacus task than for the other tasks in ch7, ch8, ch9, and ch10. Note that ch7, 8, 9,10 correspond to the frontal pole because they are more anterior in the prefrontal cortex.

Table 1 shows the p-values for the difference between the mean of the mental abacus task and that of other tasks for 7-10 channels as estimated using t-tests, as well as the Cohen's d effect sizes. A significant difference was observed between the results of the mental abacus task and those of other tasks for each channel. For channels 7-10 in the central prefrontal cortex, the Cohen's d values ranged from 0.79-3.56 for 10-year-olds and 0.85-2.83 for 6-year-olds, indicating that the effect size is quite large.

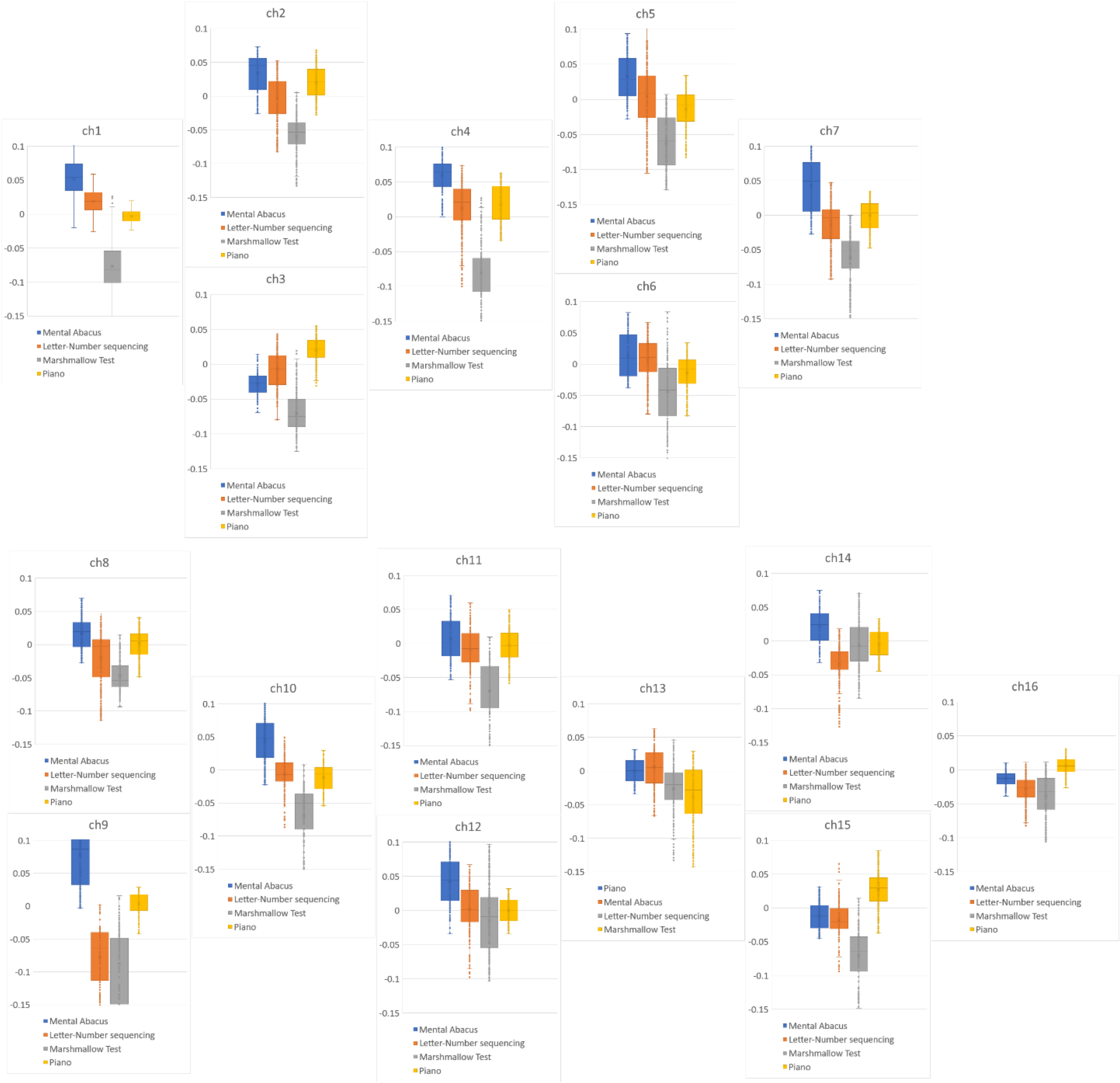

Figure 3. The result for the 6-year-old boy (Source: Author's own elaboration)

Table 1. p-values & Cohen's d effect size as estimated using a t-test for difference between mean of abacus task & other tasks

Channel			10-year-old girl		6-year-old boy	
			p-value	Cohen's d	p-value	Cohen's d
7	Mental abacus	Letter-number sequencing	<.001**	3.56	<.001**	1.42
		Marshmallow test	<.001**	3.28	<.001**	1.55
		Piano	<.001**	1.86	<.001**	1.75
8	Mental abacus	Letter-number sequencing	<.001**	1.33	<.001**	0.85
		Marshmallow test	<.001**	1.46	<.001**	1.69
		Piano	<.001**	1.61	<.001**	0.95
9	Mental abacus	Letter-number sequencing	<.001**	2.13	<.001**	2.83
		Marshmallow test	<.001**	0.79	<.001**	1.74
		Piano	<.001**	1.71	<.001**	1.93
10	Mental abacus	Letter-number sequencing	<.001**	1.69	<.001**	1.42
		Marshmallow test	<.001**	1.01	<.001**	1.49
		Piano	<.001**	2.64	<.001**	1.88

Note: †p<0.1; *p<0.05; & **p<0.01

DISCUSSION

Activation of the Frontal Pole by the Mental Abacus Task

In this study, it was discovered that the frontal pole was particularly activated in the mental abacus task. In fNIRS, with respect to Ox-Hb, increase reflects an increase in vascular bed and velocity (Haida, 2012). fNIRS validity is supported by numerous reports (Cui et al., 2011; Sato et al., 2013). Several studies used NIRS focusing on the prefrontal cortex activity, evaluating it by Ox-Hb concentration activation (Ishii-Takahashi et al., 2014; Watanabe et al., 2015; Xiao et al., 2012; Yeung et al., 2020). However, NIRS studies on implicit arithmetic are still scarce. The mental abacus is design to simulate the use of an actual abacus. Each row of the abacus consists of one bead representing the number 5 and four beads representing the number 1, and the beads are moved as needed to represent various numbers. Therefore, it is clear that this task places a considerable load on the brain.

Meanwhile, the frontal pole remains a poorly understood brain region (Tsujimoto et al., 2011). However, this region is known to play an important role in higher cognition (Burgess et al., 2007). It has also been found to be related to an individual's persistence related to goal achievement (Hosoda et al., 2020). Therefore, it is reasonable to assume that the frontal pole in the prefrontal cortex is activated by the mental abacus task, which requires a high level of executive function.

Training Executive Functions Using the Mental Abacus

Research and practice of executive function training remains elusive (Moriguchi, 2019). However, recent training studies of working memory illustrated that although working memory capacity is unlikely to change, effects generalize, and evidence for distant transitions is being collected (Jaeggi & Buschkuehl, 2012). More recently, it was demonstrated that the completion of a learning program with small goals as frontal pole training led to changes (i.e., development) of the structure of the frontal pole when the program was implemented (Hosoda et al., 2020). Therefore, it is sufficient to infer that mental abacus training may be of value for frontal pole training.

However, it is conceivable that although these effects may not be generalizable to all forms of training, mental abacus training naturally has a significant impact on problem solving in daily life. The more working memory is available, the smoother the complex problem solution becomes. However, working memory capacity has limitations. Therefore, if calculations occupy a large amount of working memory, when solving a problem, the space available for finding a solution is reduced (Willingham, 2009). In this regard, the ability to perform mental abacus training is highly effective for learning because it contributes to the space allocation of working memory and has an indirect positive effect on the utilization of working memory.

Benefits of the Study

First, the study will have a significant impact as a breakthrough in neuropsychology and cognitive psychology research because it revealed a part of the frontal pole that had not been previously elucidated. In addition, by demonstrating the value of mental abacus training, the research will have a significant impact on schools, homes, and other settings in which practical application is needed. In particular, since mental abacus is closely associated with mathematics education, its contribution to mathematics education is significant.

CONCLUSIONS

In this study, the activation of the prefrontal cortex of 6- and 10-year-old children when performing mental abacus was evaluated using a 16-channel fNIRS instrument. Compared to the letter–number sequencing task, marshmallow test, and piano task, the activation of the frontal pole was particularly noticeable when performing mental abacus task. Therefore, this study suggests that mental abacus might exhibit frontal pole training value.

Regarding the novel approaches and new insights of this paper, in order to identify high-level executive functions, I used 16-channel fNIRS to compare brain activity in the frontal pole of children with that in mental abacus and psychological tests etc.(letter-number sequencing task, marshmallow test, and piano task), and found higher activation in mental abacus, and suggested the possibility of training effects in mental abacus both at the age of 6 (younger students) and 10 (older students). Note that, considering the possibility that mental abacus promotes higher-order executive functions, it is essential to actively encourage its use in mathematics education, which has a strong connection with mental abacus. This is because mathematics is a discipline that heavily relies on computation, and frequently involves abstract concepts that requires advanced executive functioning skills.

Limitations are as follows. The measurement of brain activity is always subject to interindividual differences. However, these differences do not represent a problem in training because they are assumed to exist. Regardless, it is important to clarify that such differences exist. And the question of whether activation constitutes training is always an issue. Another issue is the amount of training is required and the resulting strength of executive function. Further research is required to answer these questions.

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Declaration of interest: No conflict of interest is declared by the author.

Data sharing statement: The data that support the findings of this study are available on request from the author. The data are not publicly available due to privacy or ethical restrictions.

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