



# Easy Abacus Calculation in Early Childhood to Support Executive Function: An Educational Pilot Case Study of Comparing Brain Activity in the Prefrontal Cortex

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The development of executive functions is remarkable in early childhood. Therefore, research on how to support the development of executive functions is actively being conducted. It has already been indicated that executive functions are related to the prefrontal cortex. Recent evidence suggests that the prefrontal cortex is involved in mental abacus (MA). Further, the study of the abacus—the base of MA—is good for not only mathematics but also nurturing the brain. However, although the abacus is easy to learn, learning opportunities have shrunk because of the widespread use of calculators. Through this educational pilot case study, I examined whether it is possible that even easy calculations during the introduction of abacus calculation in early childhood may have an effect on executive function support. I measured the activation of cerebral blood flow in the prefrontal cortex of a young child while he worked on the Wechsler Intelligence Scale for Children-IV; Working Memory Index tasks (forward digit-span task, backward digit-span task, and letter–number sequencing task); and the abacus calculation task using HOT-2000 (NeU, Japan), a two-channel wearable functional near-infrared spectroscopy device. The results revealed a significant difference between the abacus calculation task and the forward digit-span task; however, there was no significant difference between the abacus calculation task and other tasks. In other words, the brain in the prefrontal cortex was more activated in the abacus task than in the forward digit-span task. Difficulty levels were found to be in the order of the forward digit-span task, backward digit-span task, and letter–number sequencing task. Thus, there is a possibility that even simple abacus calculation has a positive effect on executive functions, especially working memory support, in early childhood. This study’s results provide a breakthrough in cognitive psychology, educational psychology, neuropsychology, and other fields related to child support, which are struggling to find valuable, practical practices for children in the field (i.e., schools and homes) beyond the laboratory.

**Keywords:** abacus, executive function, working memory, fNIRS, prefrontal cortex

## INTRODUCTION

Executive function has received much attention as an ability that is essential for success in life (Diamond, 2013; Moriguchi et al., 2016). Additionally, executive functions develop significantly during early childhood (Moriguchi and Hiraki, 2013; Watanabe, 2021a) and should, therefore, be supported during this period (Moriguchi, 2015; Watanabe, 2021b). Working memory (WM) is greatly involved in executive function (Baddeley, 2012; Zelazo and Carlson, 2012; Diamond, 2013; Saito and Miyake, 2014). Furthermore, executive function can be enhanced through intervention (Diamond and Lee, 2011; Jaeggi et al., 2011). Early intervention in WM is more effective if done during early childhood (Dehaene, 2020). There is also a relationship between executive function and the activation of cerebral blood flow in the prefrontal cortex (Moriguchi, 2008; Moriguchi and Hiraki, 2011; Watanabe, 2021a; Watanabe, 2021b). The prefrontal cortex takes a significant amount of time to mature until adolescence (Gogtay et al., 2004). During executive function tasks, the activity of the prefrontal cortex becomes stronger in late infancy (Moriguchi, 2015). In the field (schools, childcare sites, and homes), it is desirable to support executive functions in a way that is easy, including its measurement and content, rather than through laboratory methods. If the possibility of support is not suggested in the first place, it is of little use in the field. Therefore, it is desirable that the content and method be simpler (Watanabe, 2021a; Watanabe, 2021b). In education, in terms of the support of executive functioning, it has been suggested that for progress to be made, scientists must engage with teachers and schools and that parents, teachers, and researchers must work together to conduct systematic and rigorous research to continue to find effective strategies based on scientific evidence (Dehaene, 2020).

In recent years, in China and Japan, it is said to be related mental abacus (MA) and executive functions. MA is based on the abacus calculation method but is done without an abacus (Frank and Barner, 2012). Accurate MA performance can lead to improved math calculations and will aid children's math learning. Furthermore, MA can support WM (Hatano and Osawa, 1983; Tanaka et al., 2002; Lee et al., 2007; Chen et al., 2011; Dong et al., 2016; Weng et al., 2017; Kamali et al., 2019). WM has been found to be related to the prefrontal cortex (Petrides, 2000; Curtis and D'Esposito, 2003; Narayanan et al., 2005; Funahashi, 2017). When the load on the WM is excessive, the activation is small. And when the load is small, the activation is small. On the other hand, when the task is moderately difficult, activation is large (Watanabe, 2008). Because MA is designed with an abacus in mind, rather than mental arithmetic, having an understanding of abacus calculation is a prerequisite for MA. Additionally, introducing abacus calculation is easy, even for young children (5–6 years old) who can recite, read, and write numbers.

“Abacus” is *soroban*, and “abacus calculation” is *shuzan* in Japanese. An abacus is a calculating aid. A ball is located on a skewer and can be moved up and down, and the position of the ball is used to express a number. An abacus can be used for addition, subtraction, multiplication, and division. In Japan, it is

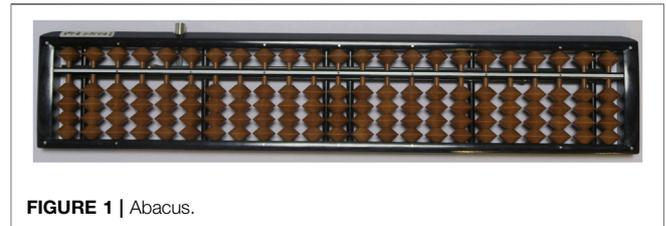


FIGURE 1 | Abacus.

common to have one 5-ball and four 1-ball abacus (Figure 1). Currently, the abacus is formally taught in third and fourth grades of elementary schools in Japan but for only 2–3 h. However, the abacus became an important factor for finding employment at banks and other clerical jobs in the country during the 1960s (Sumitomo Life Insurance Company, 1986), and this was so common that companies held abacus competitions (Matsushita Electric Industrial Co., Ltd., 1986). However, the value of the abacus has been decreasing since the 1970s, as calculators became more popular in homes because of their better performance and lower prices. For example, the number of test takers for the abacus exam peaked at 2.05 million in the 1980s and dropped to 180,000 in 2005 (Kaneshima, 2010). Therefore, around 1985, to curb the threat of the spread of calculators, people began to argue about the difference between calculators and the *soroban* (Hakamada, 1984). Furthermore, with the development of brain science, it was claimed that the *soroban* is effective for “right brain” education (Kubo, 1986), and even now, it continues to be advertised in this manner in published works (Horino, 2006; Kou, 2018). Although there is little or no evidence for abacus use, its relationship with the prefrontal cortex has been suggested (Sawaguchi, 2013). Conversely, some brain science evidence has been amassed regarding the value of MA. For example, the prefrontal cortex is activated by MA (Tanida et al., 2004). This is especially true for beginner students. (Chen et al., 2006).

Brain activity can be measured using magnetoencephalography (MEG), electroencephalography (EEG), magnetic resonance spectroscopy (MRS), positron emission tomography (PET), functional near-infrared spectroscopy (fNIRS), and functional magnetic resonance imaging (fMRI). In recent decades, the use of fNIRS has been rapidly increasing because of its safety, portability, and flexibility. fNIRS can be used for both newborns and the elderly and can be used inside and outside the laboratory (Pinti et al., 2020). fNIRS is a non-invasive neuroimaging technique that uses near-infrared light to measure changes in the concentration of oxygenated hemoglobin (oxyHb) and deoxygenated hemoglobin (deoxyHb) in the brain tissue (Ferrari and Quaresima, 2012; Scholkmann et al., 2014). Furthermore, in recent years, wearable fNIRS has also been utilized (Pinti et al., 2015; Pinti et al., 2020). Among wearable devices, the use of a two-channel device, which is inexpensive, has also become popular (Keshmiri et al., 2017; Keshmiri et al., 2018; Komuro et al., 2018; Nozawa and Miyake, 2020; Watanabe, 2021a; Watanabe, 2021b). Thus, the use of the two-channel wearable fNIRS device is ideal if it needs to be used for children and in everyday situations outside the laboratory.

To begin with, handling an abacus is not complex; however, it is difficult to conduct a clinical effort on a large scale away from the laboratory, such as at home. An educational pilot study is suitable and useful for deriving the hypothesis and is thus the approach used in this study (George and Bennett, 2005; Yin, 2014). Moreover, as a first step in testing the hypothesis, this study was conducted with a single subject to explore the possibilities. In the field, it has been previously highlighted that there are situations in which a single study is more valuable (Kawai, 2013).

Hypothesis (1): Even a simple abacus calculation has the potential to be useful in supporting executive functions (especially the part about WM.).

## MATERIALS AND METHODS

### Research Design

To test the hypothesis, I decided to use the case study approach. Then, for verification of one young child, brain activity in the prefrontal cortex was measured for each task using fNIRS. Further, the value of brain activity for each task (total Hb in the left and right prefrontal cortex) was measured. Then, the average value of each task was calculated. To compare the mean values, a test of difference of means (t-test) was performed using IBM SPSS Statistics ver. 27.0.1.0.

WISC-IV was used as the index task, and the abacus task was used as the comparison task. In other words, I examined the characteristics of a young child's brain activity using the behavioral evidence of WISC-IV and compared it with brain activity in the abacus task as an index.

### Target

The subject of the study required a young child who was just beginning to learn abacus calculation. Therefore, the subject of the study was a 5-year-old child attending a typical kindergarten. He was neither attending a special learning school nor was he in need of any special assistance. At the age of 5, he began attending an abacus school twice a week, but he had not yet learned MA. To reduce bias as much as possible, I selected subjects who had participated in brain activity measurement experiments before and who had established a trusting relationship with the experimenter. I explained the research to the parents of the child orally and in writing and obtained their informed consent before conducting the study. Additionally, a report was submitted to the University Committee for Regulations for Behavioral Research with Human Participants at the author's university. The experiment was conducted at the subject's home. Note that the introduction of abacus calculation should be practiced at an appropriate level for an individual because it is not just numerical calculation. The activation of the prefrontal cortex by abacus may lead to the acquisition of executive functions. In other words, the purpose of this study was to moderately activate the prefrontal cortex through abacus learning. Furthermore, notably, the subject was my own child. This means that the authors were teachers and childcare providers (with teaching experience, licenses, and certifications), university teachers and researchers (pedagogues, cognitive psychologists, and

neuropsychologists), and his parent. In other words, the aim was to create a close collaboration among researchers, teachers, and parents in research and practice.

### Ethics

This study was performed in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). It was approved by the Kwansai Gakuin University Committee for Regulations for Behavioral Research with Human Participants (Approval Number: 2020-06; Approval Date: June 12, 2020). Written informed consent was obtained for experimentation with human subject. The privacy rights of the human subject was safeguarded.

### Task

#### WISC-IV-Working Memory Index Task

##### *Digit-Span Task*

*Forward Digit-Span Task.* In this task, the experimenter reads out a sequence of numbers to the subject; afterward, the subject orally repeats the numbers in that order. The total number of questions is eight. Each question is further divided into two sub-questions that comprise two sequences of the same length. The length of the sequence consists of two-to nine-digit questions, which was initially two digits, and increases by one digit after each question. If the score is 0 in both series of questions (both sub-questions), the tasks will be aborted.

*Backward Digit-Span Task.* In this task, the sequences of numbers are read out by the experimenter to the subject; afterward, the subject orally repeats the numbers in the reverse order. The number of questions is eight. Each question is further divided into two sub-questions comprising two sequences of the same length. The length of the sequence consists of two-to eight-digit questions, beginning with two digits and then increasing by one digit after each question. However, the second question does not increase by one digit and remains in two digits. If the score is 0 in both series of questions (both sub-questions), the tasks will be aborted.

##### *Letter-Number Sequencing Task*

In this task, the experimenter reads out a sequence of several letters in numerals and hiragana. The subject has to sort the numbers in ascending order and the letters alphabetically and then answer orally. The number of questions is 10. There are three sub-questions in the core problem. The sub-questions comprise three series of equal length: two two-digit questions, three three-digit questions, two four-digit questions, and one each of five-digit, six-digit, and seven-digit questions. The test will be aborted if the score reaches 0 on all of the sub-questions of each question.

##### *Abacus Calculation*

The calculation content is as follows.  $3 + 2$ ,  $3 + 4$ ,  $8 + 1$ ,  $4 + 4$ ,  $4 + 2$ ,  $10 + 5$ ,  $17 + 2$ ,  $16 + 2$ ,  $15 + 4$ ,  $18 + 1$ ,  $9 + 5$ ,  $6 + 7$ ,  $3 + 9$ ,  $6 + 5$ ,  $2 + 9$ ,  $9 - 4$ ,  $7 - 3$ ,  $8 - 3$ ,  $8 - 6$ ,  $9 - 3$ ,  $13 - 3$ ,  $18 - 5$ ,  $13 - 1$ ,  $19 - 2$ ,  $18 - 3$ ,  $17 - 9$ ,  $13 - 9$ ,  $11 - 3$ ,  $16 - 7$ , and  $12 - 7$ .



**FIGURE 2** | Child calculates the task with an abacus.

## Protocol

The protocol was as follows. First, I selected a suitable subject for the study such as “early learners of the abacus.” In this case, it was necessary to build sufficient rapport. However, as it was a parent and child, no special time was necessary to build such rapport. Meanwhile, it was necessary to implement the task in a relaxed situation. Thus, the task was conducted at the subject’s home and at the desk where he usually studies. It was also determined that the subject had previously experienced brain activity measurements. In addition, if there was a request to use the restroom or take a break before/during the task, the subject was permitted to do so. If the subject was in the middle of the task, then he simply had to start the task from the beginning. Each task was conducted in a series of steps (about 1 hour) with no long breaks.

## WISC-IV-WMI Task

This task was performed according to the procedure described in the general manual (Wechsler, 2004). The forward digit-span task, backward digit-span task, and letter–number sequencing task were performed in that order. The task was completed when the “cancel” condition was met. Thus, the time for task execution differed. Moreover, brain activity during the child’s activities was measured.

## Abacus Task

There were 30 questions in total. There was no time limit. Brain activity during the child’s activities was measured (Figure 2). The order of the tasks was as follows: abacus calculation, forward digit-span task, backward digit-span task, and letter–number sequencing task. A break of at least 30 s was taken between each task.

## Calculation

This study tested Hypothesis 1 using the case study approach. Then, for verification of one young child, brain activity in the prefrontal cortex was measured for each task using fNIRS. The value of brain activity for each task (total Hb in the left and right

prefrontal cortex) was measured. Then, the average value of each task was calculated. To compare the mean values, a test of difference of means (t-test) was conducted using IBM SPSS Statistics ver. 27.0.1.0.

Cerebral blood flow in the prefrontal cortex of the young child was measured with HOT-2000, a two-channel fNIRS device made in Japan, priced at 198,000 yen. As HOT-2000 is a wearable device, it can be used outside the laboratory and even at home.

The measurement principle of HOT-2000 is as follows. Changes in blood flow associated with brain activity are monitored using near-infrared light. Blood flow increases near the area where the brain is active. Two sensor blocks are implanted in the part of the brain that targets the prefrontal cortex. The light of a wavelength of approximately 800 nm is used. The detectors are located at approximately 1 and 3 cm from the light beam. With each index of brain activity, the change in total Hb (left–right) is determined. The value is calculated by subtracting the signal at SD distance 1 cm from the signal at SD distance 3 cm at a certain rate. Spike noise has been removed. Therefore, the total hemoglobin change (left–right) was adopted as the measured value.

The baseline correction was set at 0 in the beginning, and the average brain activity during the task was examined  $\{[\sum(f(x) - \min f(x))/\text{total number of milliseconds}], x: \text{time}, \text{ and } f(x): \text{total hemoglobin}\}$ . Total hemoglobin was acquired every millisecond.

## RESULTS

This study explored the actual situation of one child. Thus, it was a within-individual comparison based on repeated experimental data.

The numerical and average values for each of the abacus calculation task, forward digit-span task, backward digit-span task, and letter–number sequencing task are as shown in **Table 1**.

For the left lateral brain activity, the mean values were, in increasing order, the forward digit-span task, backward digit-span task, abacus calculation task, and letter–number sequencing task. For the right lateral brain activity, the mean values were, in increasing order, the forward digit-span task, abacus calculation task, backward digit-span task, and letter–number sequencing task.

**Table 2** illustrates the results of a significant difference in the t-test owing to the difference between the mean values for the left and right brain activities in each task. There was a significant difference between abacus calculation and forward digit-span task. There was no significant difference between the abacus calculation task and the backward digit-span task or letter–number sequencing task.

**Table 3** shows the effect size (Cohen’s *d* and Hedges’s *g*) corresponding to the difference between the mean values for the left and right brain activities in each task. The effect size of Cohen’s *d* and Hedges’s *g* was large in the relationship between abacus and the forward digit-span task.

The result indicate that the abacus moderately activates the prefrontal cortex, as the abacus is more demanding than the forward digit-span task and it provides support with a load

**TABLE 1 |** Numerical and average values for each of the Abacus, forward digit-span, backward digit-span, and letter–number sequencing tasks.

	Abacus		Forward digit-span		Backward digit-span		Letter–number sequencing	
	Left	Right	Left	Right	Left	Right	Left	Right
1st	0.268466	0.414732	0.2325	0.197751	0.141872	0.422138	0.147612	0.425169
2nd	0.53505	0.555675	0.212778	0.167159	0.114199	0.232552	0.442409	0.575447
3rd	0.282273	0.389903	0.167282	0.361327	0.434217	0.44249	0.629194	0.504194
4th	0.4165	0.398729	0.377778	0.304672	0.8174	0.573821	0.509387	0.621678
5th	0.447747	0.311879	0.273544	0.273651	0.400166	0.469185	0.404723	1.33256
Ave.	0.390007	0.414184	0.252776	0.260912	0.381571	0.428037	0.426665	0.69181

**TABLE 2 |** T-test values for each task.

		Forward digit-span		Backward digit-span		Letter–number sequencing	
		Left	Right	Left	Right	Left	Right
Abacus	t-value	2.214	2.89	0.062	–0.203	–0.389	–1.649
	p-value	0.058 <sup>†</sup>	0.02*	0.952	0.844	0.708	0.138
Forward digit-span task	t-value			–0.977	–2.544	–1.996	–2.575
	p-value			0.357	0.035*	0.081 <sup>†</sup>	0.033*
Backward digit-span task	t-value					–0.301	–1.527
	p-value					0.771	0.165

<sup>†</sup>p < 0.1, \*p < 0.05, \*\*p < 0.01.

**TABLE 3 |** Cohen's d and Hedges's g for each task.

		Forward digit-span		Backward digit-span		Letter–number sequencing	
		Left	Right	Left	Right	Left	Right
Abacus	Cohen's d	1.400	1.828	0.039	–0.129	–0.246	–1.043
	Hedges's g	1.264	1.650	0.035	–0.116	–0.222	–0.942
Forward digit-span	Cohen's d			–0.618	–1.609	–1.262	–1.628
	Hedges's g			–0.558	–1.452	–1.138	–1.470
Backward digit-span	Cohen's d					–0.190	–0.966
	Hedges's g					–0.172	–0.872

equivalent to that of the backward digit-span or letter–number sequencing task.

## DISCUSSION

### Value of the Research

Currently, executive function support is important for young children (Moriguchi, 2015; Watanabe, 2021b). However, there are indicators that providing this support is somewhat difficult. Further, the need for this support is based on scientific evidence, not just behavioral evidence. Therefore, increasing attention is being paid to brain science research. From the perspective of supporting children, there are high expectations for the future use of wearable devices such as fNIRS instruments.

In this study, I focused on the abacus, which has not been studied much as a subject in terms of executive function (EF) support. The study of MA has attracted much attention in recent years; however, for some reason, the abacus, which is the base of MA, has not received much attention. Nonetheless, the abacus is markedly easier to introduce in terms of support.

The WISC-IV tasks of forward digit-span, backward digit-span, and letter–number sequencing are basically difficult in this order. Furthermore, the possibility of measuring children's brain activity with fNIRS brain activity has also been highlighted (Watanabe, 2021a; Watanabe, 2021b).

Based on these findings, the following hypothesis was considered.

Hypothesis (1): Even a simple abacus calculation has the potential to be useful in supporting EFs (especially the part about WM.). The possibility of this hypothesis was tested in a

case study on one young boy. The results of the iterative experiment and comparison of the intra-individual data suggested the following.

In this regard, the mean value of the WISC-IV task results shows that the order of difficulty is as follows: forward digit-span task, backward digit-span task and letter-number sequencing task; this indicates the accuracy of the results of the brain activity measurement. In particular, there is a significant difference in the test results between forward digit-span task and letter-number sequencing task, so there is a considerable difference between the two. In conjunction with these, the mean value of the abacus task is equivalent to that of the backward digit-span, and the test results show that abacus has a significant difference with the forward digit-span. In other words, it is assumed that the brain activity during abacus calculations is more equivalent to the backward digit-span task than the forward digit-span task. Additionally, the brain is not activated by content that it already knows or does not know but is loaded when the content is moderate. Considering these points, it can be observed that the abacus is more demanding than the forward digit-span task and provides support with a load equivalent to that of the backward digit-span or letter-number sequencing task.

The abacus has been highlighted as being effective for the “right brain,” but scientific evidence has been lacking. In this study, I was able to highlight the abacus as having possible value in supporting EFs. This is because the prefrontal cortex is moderately activated during abacus calculations. Furthermore, it can be stated that the measurement of brain activity in the prefrontal cortex by fNIRS can be used effectively in abacus tasks, and the possibility of its support can be explored. That is, it is important to note that it is easy to measure EF at home and in the field and that it is possible to support executive function. We can measure cerebral blood flow based on indicators that have behavioral evidence; then, we can also measure and compare the subject matter of the targeted support to derive the possibility of that support.

Recently, in the field of education, it has been suggested that in order to make progress, scientists must collaborate with teachers and schools; moreover, parents, teachers, and researchers must collaborate to conduct systematic and rigorous research to continue to find effective strategies based on effective scientific evidence (Dehaene, 2020). Regarding this point, I was able to make a proposal that allows parents, teachers, and researchers to work together to easily use scientific evidence.

## Ripple Effects

In psychology, clinical psychology, educational psychology, and childcare, regarding support for executive functions, proposing a connection with “abacus” and being able to show that support for young children is possible at home is a new proposal and is likely to be a breakthrough.

The study of two-channel fNIRS on tasks that require some degree of freedom for young children at home is likely to be a breakthrough in neuropsychology, brain science, and educational technology, as it will further expand the scope of research.

In the field of education, research and practice that unite researchers, teachers, and parents is desired. However, the integration of these three parties is quite difficult. In this study, instead of integrating three independent parties, the three parties were the same person. Although there are few such research methods, they are valuable enough if used as a model case. As a method of incorporating research results from neuropsychology, brain science, and educational technology into the field of education, the above method is quite an innovative research method, and if similar research results are acquired, it is highly likely that research will make rapid progress.

## Limitations

This research has some limitations. This is a case study; thus, there is a possibility of bias in the trend. As it has been indicated that there are large individual differences in the measurement of cerebral blood flow, further large-scale studies are needed. Additionally, only WMI was used as an index of WM. Thus, it is necessary to expand the scope of the study to include other indicators. Finally, only the data of activation of cerebral blood flow in this study is not sufficient evidence of improvement in executive function; therefore, behavioral evidence and continuous measurements are necessary.

## DATA AVAILABILITY 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.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Kwansai Gakuin University Committee for Regulations for Behavioral Research with Human Participants (Approval Number: 2020-06; Approval Date: June 12, 2020,2020). Written informed consent to participate in this study was provided by the participants’ legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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## REFERENCES

- Baddeley, A. (2012). Working Memory: Theories, Models, and Controversies. *Annu. Rev. Psychol.* 63, 1–29. doi:10.1146/annurev-psych-120710-100422
- Chen, F., Hu, Z., Zhao, X., Wang, R., Yang, Z., Wang, X., et al. (2006). Neural Correlates of Serial Abacus Mental Calculation in Children: A Functional MRI Study. *Neurosci. Lett.* 403, 46–51. doi:10.1016/j.neulet.2006.04.041
- Chen, M.-S., Wang, T.-C., and Wang, C.-N. (2011). Effect of Mental Abacus Training on Working Memory for Children. *J. Chin. Inst. Ind. Eng.* 28, 450–457. doi:10.1080/10170669.2011.610365
- Curtis, C. E., and D'Esposito, M. (2003). Persistent Activity in the Prefrontal Cortex during Working Memory. *Trends Cogn. Sci.* 7, 415–423. doi:10.1016/S1364-6613(03)00197-9
- Dehaene, S. (2020). *How We Learn: The New Science of Education and the Brain*. London, UK: Penguin.
- Diamond, A. (2013). Executive Functions. *Annu. Rev. Psychol.* 64, 135–168. doi:10.1146/annurev-psych-113011-143750
- Diamond, A., and Lee, K. (2011). Interventions Shown to Aid Executive Function Development in Children 4 to 12 Years Old. *Science* 333, 959–964. doi:10.1126/science.1204529
- Dong, S., Wang, C., Xie, Y., Hu, Y., Weng, J., and Chen, F. (2016). The Impact of Abacus Training on Working Memory and Underlying Neural Correlates in Young Adults. *Neuroscience* 332, 181–190. doi:10.1016/j.neuroscience.2016.06.051
- Ferrari, M., and Quaresima, V. (2012). A Brief Review on the History of Human Functional Near-Infrared Spectroscopy (fNIRS) Development and fields of Application. *Neuroimage* 63 (2), 921–935. doi:10.1016/j.neuroimage.2012.03.049
- Frank, M. C., and Barner, D. (2012). Representing Exact Number Visually Using Mental Abacus. *J. Exp. Psychol. Gen.* 141, 134–149. doi:10.1037/a0024427
- Funahashi, S. (2017). Working Memory in the Prefrontal Cortex. *Brain Sci.* 7, 49. doi:10.3390/brainsci7050049
- George, A. L., and Bennett, A. (2005). *Case Studies and Theory Development in the Social Sciences*. Cambridge, MA: MIT Press.
- Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., et al. (2004). Dynamic Mapping of Human Cortical Development during Childhood through Early Adulthood. *Proc. Natl. Acad. Sci. U S A.* 101 (21), 8174–8179. doi:10.1073/pnas.0402680101
- Hakamada, Y. (1984). “Dentakuto Soroban [Calculator and Abacus],” in *Syuzan to Keisanki [Abacus Calculation and Calculators]*. Editor League for Soroban Education of Japan, Inc. (Tokyo: Akatsuki-Shuppan), 23–71.
- Hatano, G., and Osawa, K. (1983). Digit Memory of Grand Experts in Abacus-Derived Mental Calculation. *Cognition* 15, 95–110. doi:10.1016/0010-0277(83)90035-5
- Horino, A. (2006). *Soroban Nyumon Doriru Unou ga Kitaerare, Imejiryoku ga Tsuku [Abacus Introductory Drills Train Your Right Brain and Develop Your Imagery Skills!]*. Kyoto: PHP Institute, Inc.
- Jaeggi, S. M., Buschkuhl, M., Jonides, J., and Shah, P. (2011). Short- and Long-Term Benefits of Cognitive Training. *Proc. Natl. Acad. Sci. U S A.* 108, 10081–10086. doi:10.1073/pnas.1103228108
- Kamali, A. M., Shamsi, F., Zeraatpisheh, Z., Kamelmanesh, M. M., and Nami, M. (2019). The Impact of UCMAS Training Program on Potentiating Cognitive Capacity Among 9–12-Year-Old Primary Schoolers in Shiraz. *arXiv* [Epub ahead of print].
- Kaneshima, H. (2010). “Noryoku Appu” Soroban Fukkatsu [Revival of Abacus “Improve Your Brain Power”]. Tokyo: Yomiuri Shinbun, 37.
- Kawai, H. (2013). *Sinri Ryoho Ronko [Psychotherapy Review]*. Osaka: Sogensya Inc.
- Keshmiri, S., Sumioka, H., Yamazaki, R., and Ishiguro, H. (2017). A Non-parametric Approach to the Overall Estimate of Cognitive Load Using NIRS Time Series. *Front. Hum. Neurosci.* 11, 15. doi:10.3389/fnhum.2017.00015
- Keshmiri, S., Sumioka, H., Yamazaki, R., and Ishiguro, H. (2018). Differential Entropy Preserves Variational Information of Near-Infrared Spectroscopy Time Series Associated with Working Memory. *Front. Neuroinform.* 12, 33. doi:10.3389/fninf.2018.00033
- Komuro, Y., Sato, Y., Lin, L., Tang, Z., Hu, L., and Sakatani, K. (2018). Reliability of Wearable Two Channel CW-NIRS in Measurements of Brain Function. In *Oxygen Transport to Tissue XL*. Cham: Springer, 301–305. doi:10.1007/978-3-319-91287-5\_48
- Kou, S. (2018). “Sorobanshiki Anzan” ga Kodomono Unou wo Kitaeru! [“Abacus-Style Mental Arithmetic” Trains Children’s Right Brain!]. Tokyo: Daiwa Shuppan.
- Kubo, J. (1986). “Unou Tanren to Soroban [Right brain training and abacus],” in *Soroban no Miryoku wo Saguru [Exploring the Appeal of the Abacus]*. Editors J. Kubo. (Tokyo: Akatsuki-Shuppan), 166–171.
- Lee, Y.-s., Lu, M.-j., and Ko, H.-p. (2007). Effects of Skill Training on Working Memory Capacity. *Learn. Instruction* 17, 336–344. doi:10.1016/j.learninstruc.2007.02.010
- Matsushita Electric Industrial Co., Ltd. (1986). “Kigyō to Soroban [Companies and the Abacus],” in *Soroban no Miryoku wo Saguru [Exploring the Appeal of the Abacus]*. Editor J. Kubo (Tokyo: Akatsuki-Shuppan), 105–109.
- Moriguchi, Y., Chevalier, N., and Zelazo, P. D. (2016). Editorial: Development of Executive Function during Childhood. *Front. Psychol.* 7, 6. doi:10.3389/fpsyg.2016.00006
- Moriguchi, Y., and Hiraki, K. (2011). Longitudinal Development of Prefrontal Function during Early Childhood. *Dev. Cogn. Neurosci.* 1, 153–162. doi:10.1016/j.dcn.2010.12.004
- Moriguchi, Y., and Hiraki, K. (2013). Prefrontal Cortex and Executive Function in Young Children: a Review of NIRS Studies. *Front. Hum. Neurosci.* 7, 867. doi:10.3389/fnhum.2013.00867
- Moriguchi, Y. (2015). Early Development of Executive Function, its Neural Mechanism and Interventions. *Jpn. Psychol. Rev.* 58, 77–88. doi:10.24602/sjpr.58.1\_77
- Moriguchi, Y. (2008). Development of Executive Function During Reschool Years. *Jpn. Psychol. Rev.* 51, 447–449. doi:10.24602/sjpr.51.3\_447
- Narayanan, N. S., Prabhakaran, V., Bunge, S. A., Christoff, K., Fine, E. M., and Gabrieli, J. D. (2005). The Role of the Prefrontal Cortex in the Maintenance of Verbal Working Memory: an Event-Related fMRI Analysis. *Neuropsychology* 19, 223–232. doi:10.1037/0894-4105.19.2.223
- Nozawa, T., and Miyake, Y. (2020). “Capturing Individual Differences in Prefrontal Activity with Wearable fNIRS for Daily Use,” in *2020 13th International Conference on Human System Interaction (HSI)*. IEEE, 249–254. doi:10.1109/HSI49210.2020.9142689
- Petrides, M. (2000). The Role of the Mid-dorsolateral Prefrontal Cortex in Working Memory. *Exp. Brain Res.* 133, 44–54. doi:10.1007/s002210000399
- Pinti, P., Aichelburg, C., Lind, F., Power, S., Swingler, E., Merla, A., et al. (2015). Using Fiberless, Wearable fNIRS to Monitor Brain Activity in Real-World Cognitive Tasks. *J. Vis. Exp.* 106. doi:10.3791/53336
- Pinti, P., Tachtsidis, I., Hamilton, A., Hirsch, J., Aichelburg, C., Gilbert, S., et al. (2020). The Present and Future Use of Functional Near-Infrared Spectroscopy (fNIRS) for Cognitive Neuroscience. *Ann. N. Y. Acad. Sci.* 1464, 5–29. doi:10.1111/nyas.13948
- Saito, S., and Miyake, A. (2014). “Jikkoukino no Gainen to Saikin no Kenkyudoko [The Concept of Executive Function and Recent Research Trends],” in *Wakingu Memori to Kyoiku [Working Memory and Education]*. Editors M. Yuzawa and M. Yuzawa (Kyoto: Kitaoji Shobo), 27–45.
- Sawaguchi, T. (2013). “Soroban de Nou no Anchieijingu wo [Anti-aging your brain with the abacus],” in *Otona no Soroban Juku [Adult Abacus School]*. Editor Tomoe-Soroban (Tokyo: Nitto Shoin), 6–9.
- Scholkmann, F., Kleiser, S., Metz, A. J., Zimmermann, R., Mata Pavia, J., Wolf, U., et al. (2014). A Review on Continuous Wave Functional Near-Infrared Spectroscopy and Imaging Instrumentation and Methodology. *Neuroimage* 85 Pt 1, 6–27. doi:10.1016/j.neuroimage.2013.05.004
- Sumitomo Life Insurance Company (1986). “Soroban ha Ningen no Kokoro Desu [The Abacus is the Human Heart],” in *Soroban no Miryoku wo Saguru [Exploring the Appeal of the Abacus]*. Editor J. Kubo (Tokyo: Akatsuki-Shuppan), 99–104.
- Tanaka, S., Michimata, C., Kaminaga, T., Honda, M., and Sadato, N. (2002). Superior Digit Memory of Abacus Experts: an Event-Related Functional MRI Study. *Neuroreport* 13, 2187–2191. doi:10.1097/00001756-200212030-00005
- Tanida, M., Sakatani, K., Takano, R., and Tagai, K. (2004). Relation between Asymmetry of Prefrontal Cortex Activities and the Autonomic Nervous System during a Mental Arithmetic Task: Near Infrared Spectroscopy Study. *Neurosci. Lett.* 369 (1), 69–74. doi:10.1016/j.neulet.2004.07.076
- Watanabe, M. (2008). “Kodo no Ninchikagaku [Cognitive Science of Behavior],” in *Ninshiki to Kodo no Nokagaku [Brain Science of Cognition and Behavior]*. Editor K. Tanaka (Tokyo: University of Tokyo Press), 203–263.

- Watanabe, N. (2021b). Response of Prefrontal Cortex to Executive Function Tasks in Early Childhood: an Exploratory Case Study for Childcare. *Ijps* 13, 12–22. doi:10.5539/ijps.v13n3p12
- Watanabe, N. (2021a). The Relationship between Executive Function and the Conservation of Quantity in Early Childhood Cognitive Processes from the Viewpoint of the Prefrontal Cortex. *Int. Elect. J. Math. Ed.* 16, em0641. doi:10.29333/iejme/10940
- Wechsler, D. (2004). *The Wechsler Intelligence Scale for children—fourth edition*. London: Pearson Assessment.
- Weng, J., Xie, Y., Wang, C., and Chen, F. (2017). The Effects of Long-Term Abacus Training on Topological Properties of Brain Functional Networks. *Sci. Rep.* 7, 8862. doi:10.1038/s41598-017-08955-2
- Yin, R. K. (2014). *Case Study Research Design and Methods (5th ed.)*. Thousand Oaks, CA: Sage.
- Zelazo, P. D., and Carlson, S. M. (2012). Hot and Cool Executive Function in Childhood and Adolescence: Development and Plasticity. *Child. Dev. Perspect.* 6 (4), 354–360. doi:10.1111/j.1750-8606.2012.00246.x

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