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RESEARCH ARTICLE

Effects of spatial program on children's mental arithmetic performance : fNIRS Study

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ABSTRACT

The purpose of this research was to analyze differences in brain region activation and changes in functional connectivity using functional near-infrared spectroscopy (fNIRS) to determine whether a spatial program improves children's mental arithmetic performance. The subjects of the study were second graders in elementary school, and a spatial program consisting of mental rotation, spatial visualization, and spatial orientation was provided. Mental arithmetic was presented in two types: numerical calculation and missing-term, with addition and subtraction. The results of the study are as follows. First, the mental arithmetic mean increased after the spatial program intervention, but increased significantly only in the missing-term task of subtraction. This shows that the spatial program has limitations in transferring to the child's numerical ability. Second, after the spatial program intervention, the brain activation areas in the DLPFC and OFC significantly decreased for addition, and the activation difference in the DLPFC and FPC was observed for subtraction. Third, in the pre-test, the functional connectivity of the brain was significantly higher between the DLPFC and FPC. In the post-test, the functional connectivity of the right hemisphere increased, and significant connectivity between channels was higher within the DLPFC region. This means that the spatial program can increase the functional connectivity of the brain and increase the complexity of neurons.

Key words: Spatial program, mental arithmetic, fNIRS, children

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Introduction

Spatial thinking is fundamental to learning and cognition (Hawes et al., 2017). Spatial ability is one of the cognitive abilities that allows us to interact with the environment and is a comprehensive ability that allows us to represent, explore, and interpret the world around us (Lowrie et al., 2017). Spatial ability is also broadly defined as the ability to generate, retain, retrieve, and transform well-structured visual images (Lohman, 1996). For example, it is knowing what shape an apple will have when cut in half in a different way than the conventional method, and knowing that what was on the right when going somewhere will be on the left when coming (Kang, 2023). These spatial abilities are used to understand, analyze, and reflect on objects, images, and relationships in space, and are especially used when learning new concepts or solving unfamiliar problems (Battista, 2007).

Spatial ability is not a single component but a combination of several components, and the commonly mentioned components through factor analysis are mental rotation, spatial visualization, and spatial orientation (Fowler et al., 2022; Kang, 2023; Lowrie et al., 2019, Ramful et al., 2017). Mental rotation is the ability to quickly and accurately perceive two dimensional and three dimensional objects when they are rotated around an axis or a point. Spatial visualization is the ability to mentally transform or manipulate the spatial characteristics of objects, and Spatial Orientation includes the concept of perspective taking, and is the ability to imagine how objects or scenes look from different perspectives.

Spatial ability plays an important role in educational success and is related to children's mathematical achievement (Judd & Klingberg, 2021; Newcombe et al., 2018). Spatial ability is linked to not only geometry, but also mental arithmetic, basic number size comparison, calculation skills, and algebra (Hawes et al., 2017). In particular, numbers are the most basic concepts covered in mathematics and are essential for learning other subjects or other areas of mathematics. Arithmetic operation are the most important skills to acquire in mathematics learning and serve as the foundation for subsequent learning (Ministry of Education, 2017). Addition is the most basic of the four basic operations in mathematics, as it is the ability to understand that the number of given objects increases. Subtraction means decreasing the number of objects by subtracting one or more numbers or quantities from a number or quantity. Repeated addition is the basis for multiplication, and repeated subtraction is the basis for division. The concepts and functions related to arithmetic operations are important content that should be covered in the elementary school 1st and 2nd grade mathematics curriculum because they correspond to the basic experience of learning mathematical structures.

The link between spatial ability and mathematical ability in children has a long history, the link between spatial ability and mathematics is not limited to spatial tasks such as geometry or measurement. Even basic number processing, such as comparing larger numbers, is closely related to spatial abilities such as mental rotation. Like the SNARC (Spatial-Numberical Association of Response Codes) effect, on the mental number line, smaller numbers are arranged on the left and larger numbers on the right, and children can predict the relative size of numbers through their spatial location. Children also tend to use their left hand to make judgments about smaller numbers and their right hand to make judgments about larger numbers when adding (Dehaene et al., 1993). Children also learn to represent numbers through spatial relationships, one way they understand symbolic numbers. They learn that 2 and 3 are close together, and 2 and 18 are far apart, so they understand that there is a big difference between the two numbers.

Spatial ability forms an important relationship with basic number representation and helps develop early number knowledge and calculation skills. Spatial ability in grades 1 and 2 predicted growth in number line knowledge over the course of a year, and spatial ability at age 5 predicted how well children performed on symbolic calculation tasks at age 8 (Gunderson et al., 2012). Mix et al., (2016) studied the relationship between spatial and math abilities in children ages 5 to 13, and found that mental rotation best predicted math achievement in younger students, while spatial visualization best predicted place value, word problems, and algebra concepts in sixth grade. Like this, spatial ability helps us intuitively understand the various meanings of numbers by using visual and spatial images, and plays an important role in forming number concepts and numerical relationships.

Spatial ability is malleable and can be improved through training (Lowrie et al., 2017). A variety of training techniques in spatial programs–video games, classroom training, and spatial task training–have been shown to improve spatial ability at all ages, but are more effective and longer lasting in younger children (Uttal et al., 2013). So can spatial training improve numerical thinking? Recently, studies have begun to demonstrate the effects of spatial programs on mathematics achievement. While there are studies showing that spatial programs lead to mathematical achievement (Cheung et al., 2019; Lowrie et al., 2017), there are mixed results in terms of transfer of spatial programs to numeracy or mathematics (Cheng & Mix, 2014; Hawes et al., 2017; Lowrie et al., 2019).

In a 3-week spatial training program, students in grades 5 and 6 improved on geometry-based graphic problems and math word problems described in a variety of sentences, but not on non-geometry graphic problems involving bar graphs, maps, and number lines (Lowrie et al., 2019). Also, a 32-week teacher-led spatial intervention program in K–2 classrooms showed improvements in spatial ability and symbolic number comparison, but not on a number knowledge test that included basic counting principles, the mental counting line, and computation skills (Hawes et al, 2017). Preschool children also showed no evidence of improvement in mathematics tasks such as counting, number comparison, number naming, and arithmetic after spatial intervention training (Cornu et al., 2017). In a study to determine whether mental rotation training improves the mathematical performance of children aged 6-8, the spatial training group showed no significant difference in number-fact problems and multidigit calculation problems, but there was a significant difference in missing-term problems and showed superior performance in the post-test (Cheng & Mix, 2014). Hawes et al (2015) extended the study of Cheng & Mix (2014) and conducted spatial training for 6 weeks on children aged 6-8, and the results showed that there was no improvement in any calculation ability including missing-term problems. Although there are no consistent research results on whether spatial training improves numerical thinking, these studies have improved our understanding of children's space and mathematics. However, many studies rely on children's behavioral responses to measure, so we still have limitations in explaining the actual thinking processes that occur in children's brains.

Cognitive processes such as space and mathematics are important research areas in neuroscience, and recent advances in neuro imaging technology have opened up the possibility of exploring the neural mechanisms underlying learning and cognition. In particular, neuroimaging technology is useful for revealing the neural mechanisms underlying cognitive load (Hosseini et al., 2017). fNIRS (functional near-infrared spectroscopy), which has been used relatively recently, is an optical imaging technology that uses near-infrared wavelengths to measure changes in the concentration of oxygenated and deoxygenated hemoglobin in the prefrontal cortex (Park et al., 2019). Light from the near-infrared range can penetrate biological tissues and is mainly absorbed by oxygenated and deoxygenated hemoglobin. In a commonly used continuous wave systems, near-infrared light is continuously transmitted into brain tissue via light emitters and then collected by light detectors. As neural activity leads to an increase in regional blood flow, combined with an increase in oxygenated and decrease in deoxygenated hemoglobin, neural activity can be inferred from changes in the concentration of chromophores. fNIRS is a non invasive brain imaging technique that is economical and portable, insensitive to motion, and offers relatively high temporal resolution. Therefore, it is suitable for use in ecologically valid settings such as schools and kindergartens. In particular, it can effectively monitor cognitive tasks such as attention, working memory, and problem solving (Ayaz et al., 2011). Therefore, since the mental arithmetic task is also a cognitive task, fNIRS can be said to be an appropriate measurement method. Looking at previous fNIRS studies related to children's mental arithmetic (Atremenko et al., 2018; Dresler et al., 2009; Soltanlou et al., 2018), most of the studies analyzed the degree of brain activity that appears when solving the four basic arithmetic operations task targeting school-age children or investigated the changes and degree of activation in multiplication ability that appear after multiplication training.

It is difficult to find fNIRS studies on whether spatial training improves mental arithmetic, despite the clear relationship between spatial ability and mathematics. Also, the results of spatial programs on arithmetic performance are inconsistent. This is because math tests tend to combine space and mathematics, or include verbal elements in mathematics. For example, math tests are presented as number lines, bar graphs, or word problems, requiring verbal understanding first. The study presented the math test as an equation, a nonverbal exact arithmetic test that excludes spatial ability, to check whether the effects of the spatial program are transferred to mental arithmetic performance. In order to minimize the spatial element, we required mental arithmetic that limited the use of fingers or concrete objects. However, the missing-term problem was included in an attempt to reproduce the studies of Cheng & Mix (2014) and Hawes et al (2015), which presented different results.

Therefore, in this study, to verify whether the spatial program is effective in improving mental arithmetic performance, two types of equations were presented: number calculation and missing-term. It also wanted to find out how children solve mental arithmetic tasks and which brain regions are activated and interact with each other in the process. Thinking activities in the brain are not limited to a single specific region, but rather are activated in multiple regions and form functional networks between regions. Therefore, this study analyzed whether children's mental arithmetic ability could be improved through educational intervention using a spatial program. In the process, it analyzed which brain regions were activated and changed, and how the functional connectivity of the brain changed before and after the spatial program intervention using fNIRS.

Methods

Participants

This study analyzed the changes in brain activation and functional connectivity that occur when children solve mental arithmetic tasks through a spatial program. The subjects of the study were second graders in an elementary school located in City A. This is an important period in elementary mathematics education to learn carrying and borrowing. During this period, basic concepts of space and mathematics are acquired, and the neurocognitive foundation for arithmetic changes according to development is formed (Artemenko et al., 2018). Before the study began, permission from the relevant educational institution was obtained, and the purpose of the study, program content, fNIRS measurement method, privacy protection, and withdrawal of consent were explained to the parents, and written consent forms were provided. Children must be able to communicate normally and must not have undergone neurological surgery or treatment. The average age of the study subjects was 7.56 years, and 24 children agreed to participate in the study. Among the 24 children, 4 children were pilot tested, 1 child transferred schools during the research, and 4 children were excluded from the analysis due to signal interruption or weak signal during the measurement, a total of 9 children were excluded, and the final study subjects were 15. Approval was obtained from the IRB of the researcher's institution before the study was conducted.

Spatial Program

The spatial program selected mental rotation, spatial visualization, and spatial orientation as spatial ability components based on related previous studies (Hawes et al., 2017; Hegaty & Waller, 2004; Kang, 2023; Lowrie et al., 2019; Linn & Peterson, 1985; Ramful et al., 2017). Mental rotation is the ability to imagine the appearance of a two-dimensional or three-dimensional object when it is rotated around an axis or a point, and spatial visualization is the ability to reconstruct the shape of a space mentally and structurally to find the appropriateness of the position of each shape. Spatial orientation is the ability to imagine the appearance of an object from a different perspective in space by changing the perspective. The spatial program is based on the 2nd grade elementary mathematics curriculum and is linked to the content of the 'Various Shapes' unit. It was conducted using various solid figures, building blocks, tangram, colored paper, and geoboard presented in the elementary mathematics curriculum.

The spatial program applied the van Hieles learning model, which has 5 phases of teaching process: inquiry, guided orientation, explication, free orientation, and integration (Gutierrez & Jaime, 1998; Pujawan et al., 2020; van Hieles, 1999). Inquiry confirms students' prior knowledge and introduces ideas for them to think about. Guided orientation is carefully guided by the teacher, and students explore and manipulate objects. Explication is when students explain what they have discovered, and the teacher elicits students' thinking through questions. Free orientation is when students find their own various problem-solving methods. Integration is when students review and recall what they have learned, and the teacher helps students integrate concepts. The spatial program consists of 14 lessons, including 5 mental rotations, 5 spatial visualizations, and 4 spatial orientations.

Table 1. Spatial program contents for each lesson

Lesson	Title	Contents	Lesson	Title	Contents
1(SV)	Location and orientation	Understanding the relation of shapes to one another based on location and orientation	8(MR)	Flip over	Draw the shape that appears when you flip the pentomino
2(SV)	Congruence	Representing the same shape on a geoboard	9(MR)	Rotate	Draw the shape that rotates a pentomino 90°, 180°, 270°
3(SV)	Part and whole	Making Larger Shapes from Smaller Shapes	10(MR)	Let's Spin Board Game	Find the same shape when rotated in the game
4(SV)	Composing Shapes	Composing Shapes to Create Pictures	11(SO)	Shapes that a friend sees	Draw the shape of an object that a friend sees
5(SV)	Covering Shapes	Covering Shapes in Different Ways	12(SO)	Draw three dimensional figures	Draw the shape of a three dimensional figure viewed from the front, side, and top
6(MR)	Mirror Play1	Understanding reflection symmetry around the vertical axes	13(SO)	Stacking Blocks1	Draw the shape of the opponent's stacking blocks
7(MR)	Mirror Play2	Understanding reflection symmetry around the horizontal axes	14(SO)	Stacking Blocks2	Draw the shape of the stacking blocks in the four directions: east, west, south, and north

* SV: Spatial Visualization, MR: Mental Rotation, SO: Spatial Orientation

The content validity was verified by one elementary mathematics expert and three elementary school teachers with a master's degree or higher and more than 15 years of teaching experience. The spatial program was conducted separately in an after-school classroom, and was directly implemented by a teacher with a master's degree in elementary mathematics who had experience over 3 years an elementary school teacher. Each lesson took about 45 minutes and was conducted once a week(see, Table 1).

Mental Arithmetic Task

This study analyzed previous studies to determine whether spatial program changes children's mental arithmetic abilities (Artemenko et al., 2018; Cheng & Mix, 2014; Hawes et al., 2015; Lowrie et al., 2019; Newman et al., 2021) and based on the 2015 revised elementary mathematics curriculum in Korea. The mental arithmetic tasks consisted of equations for addition and subtraction, and were presented in two types: number calculation and missing-term. In order to analyze brain activity that appears during the mental arithmetic solution process, tasks with carrying and borrowing procedures were presented rather than mental calculation and automatic retrieval.

Addition consists of 8 tasks in total, with the sum being 11 or more, 4 number calculation tasks (a+b=__) and 4 missing-term tasks (a+__=c). The number calculation tasks in addition consist of single-digit number calculation tasks(e.g., 8+9=__) and two-digit number calculation tasks(e.g., 34+7=__). The missing-term tasks in addition consist of single-digit(e.g., 7+__=16) and two-digit(e.g., 6+__=34) answers. Subtraction also consists of 4 number calculation tasks(a-b=__) and 4 missing-term tasks(a-__=c), for a total of 8 tasks. The correct answers for the number calculation tasks in subtraction consist of one-digit numbers (e.g., 16-7=__) and two-digit numbers (e.g., 34-8=__). The correct answers for the missing-term tasks in subtraction consist of only one-digit numbers(36-__=27). Pure decades(e.g., 20) were excluded from the tasks (Artemenko et al., 2018). The mental arithmetic task consisted of 1 practice task and a total of 16 tasks, including 4 tasks on addition number calculation, 4 tasks on addition missing-term, 4 tasks on subtraction number calculation, and 4 tasks on subtraction missing-term. All tasks were multiple choice, and 1 point was given for a correct answer and 0 points for a wrong answer, and there was no feedback. The post-test was the same as the average correct answer of the pre-test, and the same type of tasks with similar difficulty were presented. The test-retest reliability was .79. Each task consisted of only black numbers and equal signs on a white background to prevent differences in brain activity due to the background. An example of the task is shown in Fig. 1.

8 + 9=__	4 +__=11	16—7=__	13—__= 7
① 16 ② 15 ③ 18 ④ 17	① 9 ② 15 ③ 7 ④ 8	① 8 ② 6 ③ 11 ④ 9	① 4 ② 7 ③ 5 ④ 6
Addition: number calculation	Addition: missing-term	Subtraction: number calculation	Subtraction: missing-term

Fig. 1. Examples of mental arithmetic task

The appropriateness, difficulty, and time required for the items were confirmed through pilot testing. In the pilot test, it was suggested that the four possible answers for multiple choice questions should be presented as various numbers rather than continuous numbers. Since the deviation in the solution time for the mental arithmetic task was large, the presentation time for each task was limited to 1 minute. The order of the task presentation followed the advice of experts to present easy tasks first to motivate children. Therefore, the number calculation problem of addition, which had a high accuracy rate in the pilot test, was presented first, and the rest were presented randomly by task type. The intertask reliability coefficient for this test was Cronbach's alpha .83. All tasks were created with E-prime (v.3.0).

fNIRS Data Collect

The location for measuring brain activation for mental arithmetic was selected as a quiet place in an educational institution where the light could be controlled. The progress, precautions, and tasks were explained to the children, and their condition was checked. The tasks were presented on a monitor, and the answers were instructed to press the keyboard. A researcher sat next to the subjects and explained the measurement procedure and that they could stop if they felt any discomfort during the measurement. After the children were allowed to touch the device to become familiar with it, the device was attached. In cases where the head circumference was small, the optode was firmly attached to the scalp using a hairband. After that, the signal-to-noise ratio (SNR) of 48 channels was measured to confirm the transmitted signal. NIRSIT is a near-infrared multichannel device. The sensor location is designed to map the cerebral cortex area 3 cm deep inside the scalp where near-infrared light can pass through into 48 channels. The concentration values of oxygenated and anoxic hemoglobin are collected in each channel, allowing brain activity at the corresponding location to be measured. The light source was emitted at 780 nm and 850 nm, and the sampling frequency was set to 8.138 Hz.

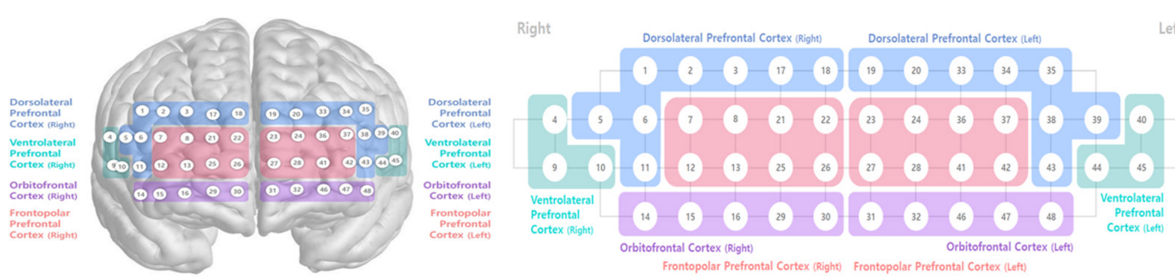

Fig. 2. Brodmann mapping of NIRSIT channels

The task for measuring brain activity for mental arithmetic was designed in the form of a Block Design. Since the block design method presents activation tasks sequentially, it can increase the reliability of the fNIRS result data by weighting the hemodynamic response that appears due to the cognitive thinking that the researcher sets as a target (Luke et al., 2021). The icon (+) was presented for 10 seconds for calibration before and after each task presentation. After guiding the start of the measurement, the subjects closed their eyes and rested for 60 seconds, then opened their eyes and gazed at the icon (+) and rested for 60 seconds. After that, each task was presented for 1 minute, and after solving the task, one of the keys 1-4 had to be pressed, and if 1 minute passed, it automatically proceeded to the next screen (see Fig. 3). The head-mounted NIRSIT developed by OBELAB Inc. was used as the fNIRS device for measuring brain activity for spatial ability.

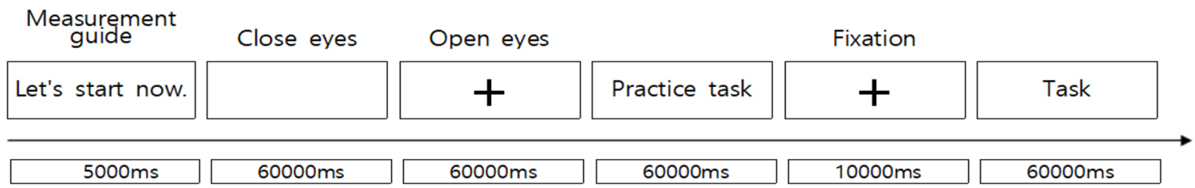

Fig. 3. Task paradigm for measuring mental arithmetic performance

Data Analysis

In order to examine the accuracy of children's mental arithmetic tasks, descriptive statistics were performed on the correct answers to the pre- and post-tasks, and then the Wilcoxon signed rank test was used. In addition, to analyze brain activation changes, NIRSIT Analysis Tool v3.8.2 and MATLAB software (R2022b) were used for preprocessing and analysis. After subject-specific marker work was performed on the raw data, noise was removed by preprocessing through a high-pass filter (DCT 0.005 Hz), a low-pass filter (DCT 0.01 Hz), and baseline setting. The changes in blood oxygenated hemoglobin and deoxy hemoglobin concentrations were calculated using MBLL (Modified Beer-Lambert Law). In particular, Oxy-Hb has a higher signal-to-noise ratio and is more sensitive to brain activation changes (Cui et al., 2011). Therefore, in this study, Oxy-Hb was used as an indicator to analyze blood oxygen concentration.

A generalized linear model (GLM) was used to calculate regression coefficients for each channel and task in the pre- and post-tests during the mental arithmetic task. In the subject-level GLM, the activation beta coefficients of each task-specific channel were extracted, and in the group-level GLM, the thermodynamic signals were extracted from channels showing significant activation by combining the beta coefficients of all participants. To analyze the difference in brain activation changes, a paired-t test was performed using the regression coefficients for each channel calculated in the pre-test and post-test. In order to analyze the brain functional connectivity, significant channels in the pre-test and post-test were calculated through one sample t-test, and Pearson's correlation coefficient was calculated to analyze the connectivity among channels. The anatomical locations, activation differences, and functional connectivity of statistically significant channels were visualized using BrainNet Viewer.

Results

Behavioral Data

To determine whether the spatial program improves children's mental arithmetic performance, the mean, standard deviation, and accuracy of addition and subtraction were calculated before and after the experiment. Then, the Wilcoxon signed rank test was used to analyze the results by task type, and these are shown in Fig. 4, Table 2.

Table 2. Behavioral results for mental arithmetic tasks

		Pre-test	Accuracy	Post-test	Accuracy	Z	*p*
		M(SD)	%	M(SD)	%		
Addition	Number calculation	3.563(.892)	89.063	3.667(.816)	91.667	.447	.655
	Missing-term	2.687(1.078)	67.188	3.133(.915)	78.333	1.164	.244
Subtraction	Number calculation	3.250(1.183)	81.250	3.400(.985)	85.000	.707	.480
	Missing-term	2.062(1.236)	51.563	2.867(1.060)	71.667	2.326	.020

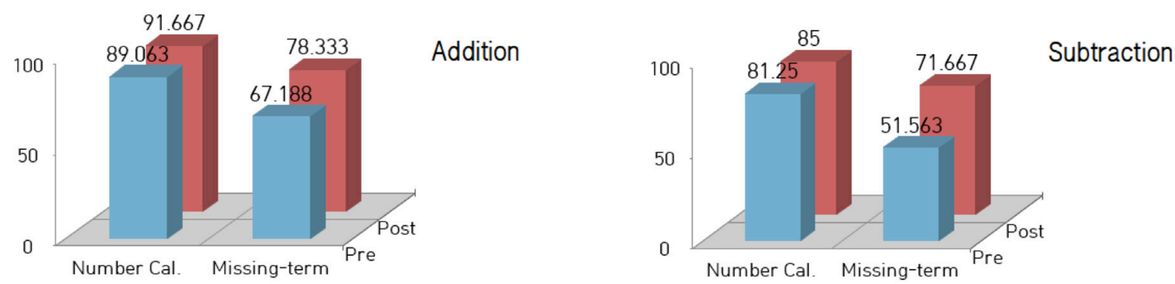

Fig. 4. Accuracy in pre-test and post-test for mental arithmetic tasks

The accuracy of mental arithmetic tasks was higher in the post–test than in the pre-test, in addition than in subtraction, and in the number calculation task than in the missing-term task. Specifically, in the pre-test, the accuracy of the number calculation task in addition was the highest at 89.063%, and the accuracy of the missing-term task in subtraction was the lowest at 51.563%. In the post-test, the accuracy of the number calculation task in addition was the highest at 91.667%, followed by the number calculation in subtraction, the missing-term in addition, and the missing-term task in subtraction was the lowest at 71.667%.

Results of analyzing the mean difference between pre- and post-test according to the type of mental arithmetic task, in addition, the post-mean (M=3.667, M=3.133) was higher than the pre-mean (M=3.563, M=2.687) in both number calculation and missing-term tasks, but there was no significant difference. In subtraction, the post-mean (M=3.400, M=2.867) was higher than the pre-mean (M=3.250, M=2.062) in both number calculation and missing-term tasks, there was a significant difference between pre-test and post-test only on the missing-term subtraction problem (z=2.326, p=.020). This means that the spatial program helped solve the missing-term task in subtraction.

fNIRS Data

To analyze the changes in brain activation areas of children before and after the spatial program in solving mental arithmetic tasks, we calculated the regression coefficients at each channel in pre-HbO2 and post-HbO2 for each task and conducted a paired-t test (see Fig. 5, Table 3).

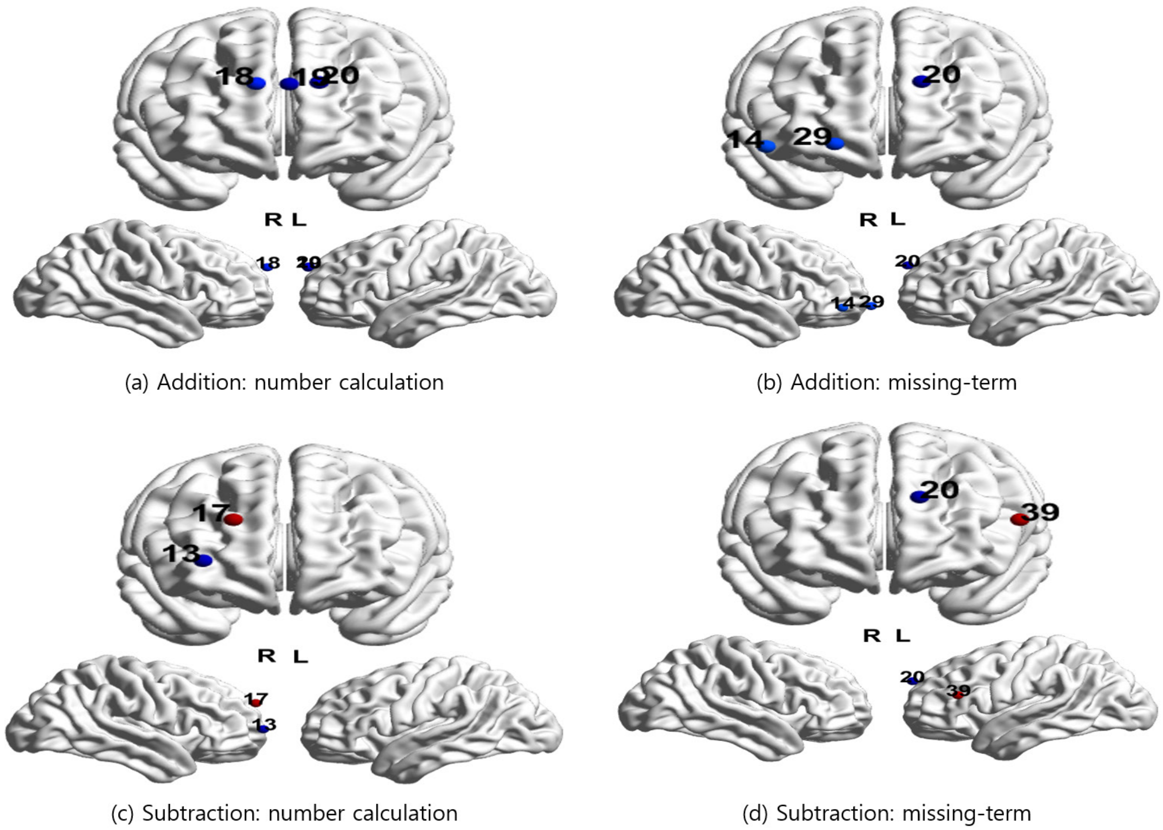

Fig. 5. Analysis of brain activation differences between pre-test and post-test in mental arithmetic tasks

Table 3. Statistical results on brain activation differences in mental arithmetic tasks

Task type		Channel	Region	BA	Hemisphere	t	*p*
Addition	Number calculation	18	DLPFC	10	R	-2.211	.044
		19	DLPFC	10	L	-2.773	.015
		20	DLPFC	10	L	-2.456	.028
	Missing-term	14	OFC	47	R	-2.205	.046
		29	OFC	10	R	-2.344	.036
		20	DLPFC	10	L	-3.207	.006
Subtraction	Number calculation	13	FPC	10	R	-2.204	.045
		17	DLPFC	10	R	2.186	.046
	Missing-term	20	DLPFC	10	L	-2.348	.029
		39	DLPFC	46	L	2.316	.036

Addition showed decreased activation in the DLPFC and OFC, while subtraction showed activation differences in the DLPFC and FPC. Looking at this in more detail, the number calculation task in addition showed a significant decrease in brain activation at ch18 ($t=-2.211$, $p=.044$) in the R-DLPFC, ch19 ($t=-2.773$, $p=.015$), and ch20 ($t=-2.456$, $p=.028$) in the L-DLPFC on the post-test. In the missing-term task of addition, brain activation was significantly decreased at ch14 (t=-2.205, *p*=.046), ch29 (t=-2.344, *p*=.036) in the R-OFC, and ch20 (t=-3.207, *p*=.006) in the R-DLPFC. In subtraction, the number calculation task indicated a significant decrease in activation at ch13 (t=-2.204, *p*=.045) in the R-FPC and a significant increase in activation at ch17(t=2.186, *p*=.046) in the DLPFC. In the missing-term task of subtraction, there was significantly decreased activation at ch20 (t=-2.348, *p*=.029), increased activation at ch39 (t=2.316, *p*=.036) in the DLPFC.

Children activated the DLPFC, FPC, and OFC regions to solve mental arithmetic task, and brain activation decreased on the post-test compared to the pre-test. That is, addition showed a significant decrease in activation in the DLPFC in both the number calculation and missing-term tasks on the post-test. However, in the subtraction task, the channels in which activation in the DLPFC significantly increased (ch10, ch39) were more than the channels in which it decreased (ch20) in both the number calculation and the missing-term task.

Functional Connectivity of Brain

To analyze whether spatial training causes changes in the functional connectivity of the brain network among brain regions in solving mental arithmetic tasks, correlation coefficients were calculated, and the results of the analysis are shown in Fig. 6.

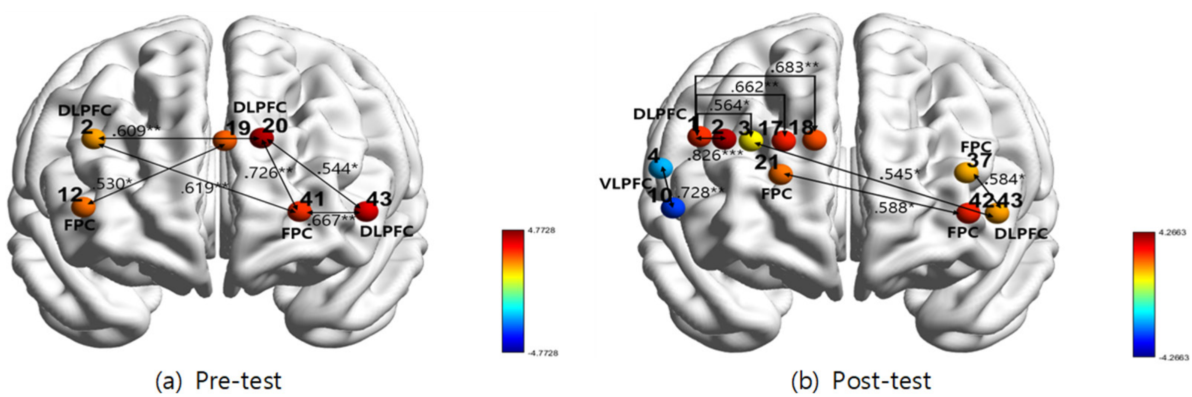

Fig. 6. Functional connectivity of brain to mental arithmetic tasks in pre-test and post-test

Looking at the functional connectivity of the brain network among brain regions shown in the pre-test, significant functional connectivity was found in the DLPFC and FPC regions. First, looking at the right hemisphere, ch2 in the R-DLPFC showed significant connectivity with ch20(r=.609) in the L-DLPFC and ch 41(r=.619) in the L-FPC. Ch12 in the R-FPC showed significant connectivity with ch19(r=.530) in the DLPFC. Looking at the left hemisphere, ch20 in the L-DLPFC showed significant connectivity with ch41(r=.726) in the L-FPC and ch43(r=.544) in the L-DLPFC. And ch41 in the L-FPC showed significant connectivity with ch43(r=.667) in the L-DLPFC.

In the post-test, functional connectivity of brain network was observed in the DLPFC, FPPFC, and VLPFC regions, and relatively more significant connectivity between channels was observed within the R-DLPFC region. Looking at the right hemisphere, ch1 in the R-DLPFC showed significant connectivity with ch2 (r=.826), ch 3 (r=.564), ch 17 (r=.662), and ch 18 (r=.728) in the R-DLPFC. Ch4 in the R-VLPFC showed significant connectivity with ch10(r=.728) in the R-VLPFC. And ch21 in the R-FPC and ch42(r=.588) in the L-FPC also showed significant connectivity. Looking at the left hemisphere, ch43 in the L-DLPFC showed significant connectivity with ch3(r=.545) in the R-DLPFC, ch37(r=.584,) in the L-FPC. That is, significant functional connectivity in the post-test was greater in the right hemisphere than in the left hemisphere, there were more intra hemispheric connections than inter hemispheric connections, and they occurred within the same brain region.

Discussion

This study analyzed brain activation differences and functional connectivity of networks among brain regions using fNIRS to determine whether spatial program improves children's mental arithmetic performance.

First, the mean of mental arithmetic was higher in the post-test than in the pre-test, but there was a significant difference between the pre-test and the post-test only in the missing-term task of subtraction. In children aged 6-8 years, the effect of mental rotation training on number facts, multidigit calculations, and missing-term problems was significantly different from that of the experimental group only in missing-term problems (Cheng & Mix, 2014). In a spatial intervention program for children aged 4-7 years, there was no significant improvement in a nonsymbolic comparison test and a measure of number knowledge (Hawes et al, 2017). And it is partially similar to the research result (Newman et al., 2021) that spatial training through block play affected the arithmetic processing of 8-year-old children and had a greater effect on subtraction than addition.

There was a significant difference in the missing-term task of subtraction after the spatial program intervention, which was less familiar than the number calculation task, and requires a mental process of moving the place to solve it. And to successfully perform subtraction, more calculations are required than addition. Children should be able to think of a variety of mathematical transformations, such as decomposing 12 into 7 and 5 or 8 and 4. Also, borrowing is needed in subtraction problems when the unit digit of the subtrahend is larger than the unit digit of the minuend. Likewise, subtraction also requires an understanding of the place-value structure of the Arabic numeral system (Artemenko et al., 2018). This computational process is likely to depend on spatial attention, transformation and translation, and spatial processing abilities according to the size of the number.

This seems to provide a cognitive process that helps transform numbers in various ways by creating a mental space in which the spatial program can represent the place value structure of numbers as an image and mentally calculate it. It is also inferred that it helped in successful performance by restructuring the missing-term problem of subtraction into an easier form. That is, the spatial program is interpreted as helping to decompose and translate numbers, spatially visualize the mental operation solving process, and increase the accuracy of the missing-term task of subtraction.

Second, the result of analyzing the difference in brain activation before and after the spatial program, addition showed decreased activation in the DLPFC and OFC, while subtraction showed activation differences in the DLPFC and FPC. In addition task, activation of the DLPFC significantly decreased in both the number calculation and missing-term tasks. Children aged 9–11 years showed significant deactivation in the DLPFC during geometric problem solving after mental rotation training (Da Silva Soares et al., 2022). And this is contextually similar to a study showing that two weeks of multiplication training decreased prefrontal brain activation in children, and that college students who underwent orienteering exercise training showed significant decreases in activation in both the L-DLPFC and R-DLPFC (Bao et al., 2022; Soltanlou et al., 2018). The DLPFC is involved in high-level executive processing such as planning, strategic processing, attention, and information monitoring and manipulation (Toepper et al., 2010). In order to perform calculations accurately, one must be familiar with the calculation algorithm, but at the same time, one must maintain concentration while planning and retrieve simple arithmetic facts from memory. At this time, the role of the frontal lobe is thought to be as a control center, maintaining working memory, selecting the correct answer, suppressing unnecessary information, and other general control processes in the field. Furthermore, the decreased activation in the DLPFC may suggest that children have found a more efficient strategy for solving the mental addition task through spatial programming. This can be interpreted as a decrease in activation and a simultaneous increase in processing efficiency due to the reduced neural resources that must be recruited. And in the missing-term task of addition, the activation at ch14 and 29 in the OFC significantly decreased in the post-test. The OFC processes information related to desire and motivation and is involved in regulating various emotional and affective behaviors and information to suit the situation (Stalnaker et al., 2015). The decrease in activation in the OFC can be interpreted as an intention to secure remaining neural resources while deactivating the emotional and affective parts during task solving, thereby focusing on solving mental arithmetic tasks.

Meanwhile, subtraction showed significant differences in the DLPFC and FPC in the post-test. In the subtraction task, the channels in which activation significantly increased (ch17, 39) in the DLPFC were more than the channels in which activation decreased (ch20) in the number calculation and missing-term tasks. In children aged 4-6 years, the Oxy-Hb concentration in the DLPFC was higher under the difficult condition of having to remember three pictures rather than two pictures (Zheng et al., 2023). Fifth graders showed greater activation in the right inferior frontal gyrus for cognitively difficult two-digit multiplication than for single-digit multiplication (Soltanlou et al., 2018). In children who were unable to solve the tangram, prefrontal cortex activation consistently increased, while in children who were able to develop a strategy, prefrontal cortex activation consistently decreased (Kuroda et al., 2009).

This is inferred to be because complex cognitive tasks require greater cognitive load, and brain activation increases in the process. In general, as mathematics complexity increases, general cognitive process areas such as working memory, sustained attention, and planning are facilitated (Mücke et al., 2018). In particular, subtraction relies on procedural processes rather than fact retrieval to solve the task (Prado et al., 2014). This makes the task more difficult and complex, and in the process, brain activation seems to increase. Increased activation means that the neural network fires more intensely or a wider area is activated. It is assumed that children explore resources intensively and widely to solve the task. In fact, in this study, the accuracy of subtraction was lower than that of addition. This result is interpreted as an increase in difficulty having a higher sensitivity and requiring additional activation in the related brain region, DLPFC, for successful task solution.

And in the subtraction task of number calculation, the channel activation in the FPC significantly decreased. FPC is a region that becomes more active as cognitive complexity increases and information processing becomes more abstract.

It is also responsible for judgment and reasoning in exploratory decision-making that plans future actions and seeks new alternatives (Burgess et al., 2007). This suggests that spatial programs support intuitive solving of complex arithmetic tasks and help mentally represent the location and borrowing of place values, thereby reducing the computational process in decision-making, thereby reducing the activation in the FPC.

Third, as a result of analyzing the changes in functional connectivity between pre- and post-tests in solving mental arithmetic tasks, the functional connectivity of brain activity was significantly higher between the DLPFC and FPC in the pre-test. The DLPFC is a cortex involved in uncertainty, is positively correlated with uncertainty, and is also related to the performance of spatial working memory tasks (McLaughlin et al., 2009). And FPC is activated when coordinating two processes that are in progress at the same time, and plays a role in coordinating and integrating DLPFC (Burgess et al., 2007). Children have more uncertainty because they cannot use concrete objects and cannot count aloud to solve mental arithmetic tasks. At the same time, the missing term task requires spatial working memory along with computational algorithms. It is inferred that there is a lot of inter-channel connectivity between DLPFC and FPC regions in the process of coordinating and integrating these two processes.

In the post-test revealed significant connectivity in the channels within the right DLPFC. This is contextually similar to the study (Bao et al., 2022) that found that after 12 weeks of directed exercise practice, the functional brain connectivity between the DLPFC of college students was significantly enhanced. The DLPFC is known to be responsible for executive functions, involved in strategic processing, and highly activated when manipulating information in working memory. Furthermore, the right DLPFC is associated with spatial memory task performance and spatial information updating (Bao et al., 2022; Kang, 2021; Schmidt et al., 2018). This shows that the right brain is being used more through spatial program, and it is inferred that mental arithmetic tasks are being solved in the process. Also children require more cognitive resources and working memory in difficult tasks that require carrying and borrowing numbers in addition and subtraction. Inefficient carrying and borrowing procedures can cause frequent errors in mental arithmetic. Therefore, it is interpreted that cognitive load is reduced by increasing activation and functional connectivity in the DLPFC region to prevent errors, and cognitive resources are evenly distributed and supported in nearby areas to focus on working memory.

Moreover, in the post-test, there was significant functional connectivity in the right VLPFC region that was not present in the pre-test, that is, when ch4 was deactivated, ch 10 was also deactivated. Ch4 and ch10 in the VLPFC correspond to BA 45, the Broca area in the right hemisphere. Language in the right hemisphere processes words based on their specific meaning rather than their general meaning, and is closely related to cognitive overload in the information processing process (Federmeier, 2007). This is interpreted as children trying to focus more on the calculation process by disabling language-related information while solving mental computational tasks.

And in the post-test, there was a lot of functional connectivity within the right hemisphere, and significant functional connectivity increased within the same region. The right hemisphere is relatively a lot involved in processing nonverbal information and spatial information. This suggests that the connectivity of the right hemisphere increased through the spatial program, proving the effectiveness of the spatial program. In particular, when equal attention is required, the activation of the right hemisphere increases more than the left hemisphere(Çiçek et al., 2007), that suggests that the right hemisphere plays a more important role in overall attention and arousal. In fact, the significant increase in accuracy in the missing-term task of subtraction is interpreted as a significant connection of relevant channels by allocating more attention to the right hemisphere, which processes spatial information.

Conclusions and Implications

First, the mental arithmetic mean of children was the highest in the number calculation of addition, followed by the number calculation of subtraction, the missing-term of addition, and the missing-term of subtraction tasks. After the intervention of the spatial program, the mental arithmetic mean of children increased, but there was a significant difference between the pre- and post-tests only in the missing-term of subtraction task, and there was no significant difference in other tasks. This shows that spatial programs have limitations in transferring to children's mental numerical abilities. However, the significant increase in the missing-term task of subtraction suggests that the spatial program supported the decomposition and transformation of numbers in subtraction and aided in the understanding of the place-value structure of the number system. Therefore, it is necessary to organically connect teaching methods for spatial and arithmetic abilities to provide meaningful learning.

Second, brain activation decreased after the spatial program intervention. Addition showed a decrease in activation in the DLPFC and OFC, and subtraction showed a difference in activation in the DLPFC and FPC. It is inferred that this helped the spatial program perceive the arithmetic task as less complex, which resulted in reduced activation. In addition task, DLPFC activation decreased in both the number calculation and missing-term tasks, but there was a channel of increased DLPFC activation only in the missing-term task of subtraction. This means that children recognized this type of task as difficult, and it seems that they increased the activation of DLPFC, which is involved in the executive processing of planning, strategic processing, attention, and manipulation, to solve it successfully.

Third, after the spatial program intervention, the functional connectivity of the brain network between brain regions significantly increased. In particular, there were many connections within the right hemisphere, and significant functional connectivity within the same region increased. The increase in functional connectivity of the right brain, which is relatively a lot involved in processing nonverbal and spatial information, is inferred to be a result of the spatial program. Also, the significant increase in functional connectivity within the DLPFC region is interpreted as an intention of children to efficiently solve mental arithmetic tasks by recycling neural resources and to increase the accuracy of task solving by distributing cognitive resources within the same region. This suggests that spatial program can increase brain connectivity and increase neuronal complexity.

This study is significant in that it analyzed changes in brain activation and functional connectivity using fNIRS, one of the brain imaging analysis methods, to determine whether spatial programming leads to improvements in mental arithmetic. However, the rigor of the study is limited by the insufficient number of subjects and the lack of division into experimental and control groups.

The educational implications are as follows. First, mathematically, both the carry and the borrow operations refer to the sum/difference of the unit digits, the sum/difference of the decade digits, and the necessary transfer between the units and decades. Thus, the borrow operation may be considered the mathematical inverse of the carry operation (Artemenko et al., 2018). However, it has not yet been studied whether carrying and borrowing actually involve the same cognitive processing. This study revealed that the DLPFC and OFC regions are involved in the carrying cognitive process, and the DLPFC and FPC regions are involved in the borrowing cognitive process. This suggests that the cognitive processes of carrying and borrowing are related but not identical.

Second, this study conducted a spatial program using concrete objects. However, in a previous study (Hawes et al., 2015) that conducted spatial training using iPad instead of concrete objects, no improvement was found in any calculation ability, including missing-terms. This suggests that the use of concrete objects may affect the solution of mental calculation tasks. Concrete manipulatives are easier for children to use and interact with than virtual manipulatives, and the extent of this interaction appears to predict performance outcomes. This suggests that the younger the students are and the more abstract the content, the more likely it is that teaching methods using concrete objects can help students form mathematical concepts.

Third, it was able to compare brain activation before and after the spatial program intervention using neuro imaging methods and directly confirm changes in the brain's functional connectivity. This could be a new alternative for evaluating the effectiveness of educational programs and could provide more specific, visual results of the brain's cognitive changes.

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