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RESEARCH ARTICLE

Brain activation region analysis for children's spatial ability: fNIRS Study

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아동의 공간능력에 대한 두뇌 활성 영역 분석: fNIRS 연구

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ABSTRACT

This study was analyzed using fNIRS to find out which brain regions were activated in elementary school students (1st-2nd) to solve spatial tasks. Spatial ability was based on mental rotation, spatial visualization, and spatial orientation, and the research results were as follows. First, in mental rotation, spatial visualization, and spatial orientation, the DLPFC was activated significantly higher, and the VLPFC was activated significantly lower. Second, OFC appeared only for spatial orienting, with significantly lower activation in both brain regions. Third, boys had significantly higher activation of many channels in the DLPFC and VLPFC, while girls had significantly lower activation of only one channel of the VLPFC. And in terms of brain activity differences between genders, boys showed higher activation in the DLPFC, FPPFC, and VLPFC than girls. The use of various brain regions in boys suggests the possibility of using more diverse strategies and seeking alternatives when solving new types of spatial tasks that are difficult or unfamiliar.

Key words: Spatial ability, fNIRS, child, mental rotation, spatial visualization, spatial orientation

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Introduction

Spatial ability is an early sign of creative thinking and has a greater relationship with future creativity and innovation ability than mathematical ability or language ability (Kell et al., 2013). This is the total ability to execute tasks related to space, the ability to see, inspect, analyze, and reflect on objects, images, relationships, and transformations in space (Battista, 2007; Linn & Peterson, 1985). This allows us to understand the logical structure of space and view things from various perspectives as the basis of human behavior, thinking, and cognition (Kang, 2023).

Spatial ability is not a single component rather it consists of several components, there is a lack of agreement about the exact components of spatial ability although it is considered multifaceted (Linn & Peterson, 1985; McGee, 1979; Ramful et al., 2017). For this reason, it is used interchangeably with terms such as spatial sense, spatial reasoning, and spatial thinking. Also, in relation to measuring spatial ability, the same term is sometimes explained with different contents, and conversely, different term are sometimes used for similar contents. For example, the term mental rotation is sometimes used to refer to the ability to rotate an object mentally, but it is also viewed as an ability included in spatial visualization (McGee, 1979), and is also used as the term for spatial relationships (Lohman, 1979). However, it presents mental rotation, spatial visualization, and spatial orientation as components commonly presented through factor analysis of spatial ability (Fowler et al., 2022; Kali & Orion, 1996; Lohman, 1979; Lowrie et al., 2019; Ramful et al., 2017).

Mental rotation is a cognitive process in which a person imagines how 2D and 3D objects would appear after it has been turned around a point by a certain angle (Shepard & Metzler, 1971). Spatial visualization requires the ability to reconstruct, decompose, and transform shapes through the processes of apprehending, encoding and mentally transforming spatial forms.

And spatial orientation includes the notion of perspective taking, which is the ability to imagine how a stimulus array will appear from another perspective. This is the ability to imagine how an object or scene looks from perspectives different to the observer's. (Lohman, 1979; Ramful et al., 2017). As such, spatial ability is an important area of cognitive ability to interact with the environment, including the ability to rotate mental images of 2D or 3D objects, the ability to predict how many different shapes will be created as a result of one or more transformations, and the ability to infer how an object looks from multiple perspectives are important ability to understand space. In particular, mental rotation and spatial visualization solve tasks based on egocentric frames of reference. In other words, they use themselves as the center of the surrounding spatial organization to think about the changed movement of objects. On the other hand, spatial orientation changes the observer's perspective based on allocentric frames of reference without changing the position of the objects (Fernandez-Baizana et al., 2021; Ruggiero et al., 2016).

Solving spatial tasks is based on the parallel cooperation of egocentric and allocentric frames of reference, and the ability to integrate these effectively appears after about 6 years of age (Nardini et al., 2006). This age, first and second grades of elementary school, is an important period of transition from the preoperational stage to the concrete operational stage. Children acquire concepts of shape and space, and acquire perspective taking skills, which are important in spatial ability (Clements et al., 2004). In addition, mental transformation of spatial information occurs around age 7, when child is in the concrete operational stage (Harris et al., 2013). Children think logically about specific events, choose appropriate spatial strategies, and use external reference frames to develop an understanding of complex topological relationships. And it is a time when numerous cognitive abilities such as attention, memory, and control of inhibition develop. During this period, we still do not know the child's thinking process that appears in the process of solving spatial tasks. Therefore, to better understand spatial ability, it is necessary to go beyond behavioral data, and a recent neuroscience approach could be an alternative.

Spatial ability is an important area of research in cognitive neuroscience, and advances in neuroimaging technology have opened up the possibility of exploring the neural mechanisms that form the basis of learning and cognition. fNIRS (functional near-infrared spectroscopy) is widely used in various studies, is a non-invasive optical imaging technology that can be used to measure changes in Oxy-Hb and Deoxy-Hb concentrations related to brain functional activities (Park et al., 2019; Scholkmann et al., 2014). fNIRS is not only safe, non-invasive, economical, and portable, but is also less sensitive to subject movement and provides relatively high temporal resolution. And due to the quiet, noise-free procedure that does not interfere with problem solving, it effectively studies other specific cognitive abilities and does not cause problems such as anxiety about unfamiliar situations restrictions such as fMRI (Soltanlou et al., 2017). Therefore, fNIRS can effectively monitor cognitive work processes, is more friendly to children who move a lot, and is portable, allowing more data samples to be collected in educational field, which is ecologically valid environments.

Looking at previous fNIRS studies related to education, in all basic arithmetic operations, 6th and 7th graders showed decreased frontal lobe activation in subtraction, which requires less effort, and the activation of the temporal lobe increased in the addition and multiplication of automatic withdrawal (Artemenko et al., 2018). Upper elementary school students showed greater activation in the right inferior frontal gyrus for double-digit multiplication than for single-digit multiplication (Soltanlou et al, 2018). First and second graders of elementary school showed significantly higher activation in DLPFC in solving the transformation geometry problem, and the group who answered all the tasks correctly showed relatively significant activation in FPPFC (Kang, 2020). A correlation analysis between mind reading task performance scores and brain activity of preschooler, elementary and middle school students showed a significant correlations with the right hemisphere OFC and the left hemisphere DLPFC, a positive correlation with the OFC and a negative correlation with the DLPFC (Kwon et al., 2021). Although fNIRS research on young children is steadily being conducted, research on brain nerve activation related to spatial ability is still insufficient.

The first year of elementary school is a time when basic concepts of space and shapes are formed and acquired, and research on spatial ability for the first and second grades of elementary school is not much, and it is difficult to find a study analyzed using brain images. Therefore, we would like to analyze children's spatial ability using fNIRS. In the current study, we consider spatial ability as an overarching term that includes the skills associated with mental rotation, spatial visualization, and spatial orientation. The purpose of this study is to examine how children solve tasks related to mental rotation, spatial visualization, and spatial orientation, which are components of spatial ability, and in which areas and how the neurophysiological responses of the brain are activated in the process.

Methods

Participants

This study was designed to analyze children's spatial ability, and the subjects were selected by simple random sampling of 3 classes each in the 1st and 2nd grades of A Elementary School located in Chung cheong buk-do. Before executing the research, the purpose of the study, fNIRS measurement method, content, and the protection of personal information were explained to the relevant educational institution, and only children with parental consent were selected as research subjects. Although 37 1st graders and 30 2nd graders agreed to participate, children who could communicate normally, right handed children, and children without neurological surgery and treatment were selected to execut spatial ability tasks. Children who gave up on measurement and children whose signals suddenly stopped during measurement were excluded. The final subjects of the research were 60 students; 33 1st graders (M=7.6 years old) and 27 2nd graderss (M=8.7 years old). This research was conducted with approval from the bioethics committee of the affiliated institution [KNUE-202209-SB-0037-01].

fNIRS Task Design

To design a task to measure spatial ability, based on previous studies (Hegaty & Waller, 2004; Lowrie et al., 2019; Linn & Peterson, 1985; Quaiser-Pohl, 2003; Ramful et al., 2017), spatial ability components were selected as mental rotation, spatial visualization, and spatial orientation. The spatial ability task consists of a total of 15 tasks, including 1 practice task for each component and 4 main tasks (Kang, 2023), and was used with modifications and supplements. Mental rotation consists of two 2D tasks and two 3D tasks. The 2D task is the Card Rotation Test (CRT), which consists of letters and animals familiar to children. The 3D task presented CCT (Cube Comparison Test), the difficulty of the task was adjusted by inserting symbols on the sides of the cube. The researcher instructed the child to find the same picture when the picture presented was turned to the right. FBT(Form Board Test) was used to measure spatial visualization, which requires finding a shape that can be created by combining 3-4 presented pieces. The researcher explained to the child to find something that could be made by combining the presented pieces. For spatial orientation, a perspective taking task was used, and the participants were instructed to find the picture that their friend was looking at. The child only has to choose one correct answer among the four examples presented. The order of presentation of each task was randomly presented for each component according to expert advice, and the least difficult question was presented as a practice question. The task presentation time is 3 minutes, 1 point if it is correct, 0 point if it is wrong, and there was no feedback. The spatial task was built with E-prime (v.3.0).

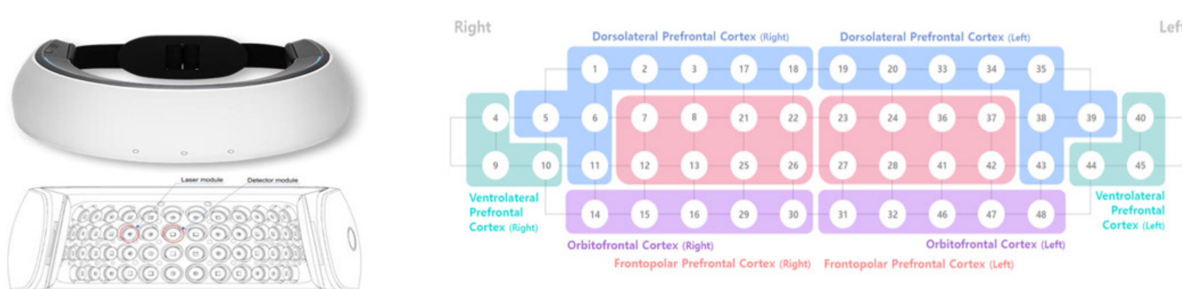

Fig. 1. NIRSIT device and Brodmann mapping of NIRSIT channels

The task to measure brain activity for spatial ability was designed in the form of a block design. Block Design is to alternately present activation tasks that include targeted brain functions and control tasks that do not (Park et al., 2019). An icon (+) was presented before and after each task was presented. After guiding the start of the measurement, the eyes were closed and rested for 60 seconds, and then the eyes were opened and rested for 60 seconds while staring at the icon (+). Each task was then presented for 3 minutes, and if 3 minutes were exceeded, the task automatically progressed to the next screen. NIRSIT, designed by OBELAB Inc., was used as an fNIRS device to measure children's spatial ability brain activity (see Fig. 2).

Experiment Procedures and Data Collect

The place to measure the brain activity of spatial ability was selected as a quiet place of educational institutions where light could be controlled. The process, precautions, and tasks were explained to the child, and the child's condition was checked. The task was presented on the computer screen, and the correct answer was guided to press the keyboard. A researcher sat next to the subject and informed them about the measurement procedure and that they could stop taking the measurement. The child touched the measuring device to become familiar with it and then attached the device. Afterwards, the signal to be transmitted was confirmed by measuring the signal-to-noise ratio (SNR) of 48 channels. NIRSIT is a near-infrared multi-channel device. The sensor location is designed to enable mapping of the cerebral cortex area 3 cm deep inside the scalp through 48 channels, where near-infrared rays can pass. Concentration values of Oxy_Hb and Deoxy-Hb are collected in each channel, allowing brain activity at that location to be measured.

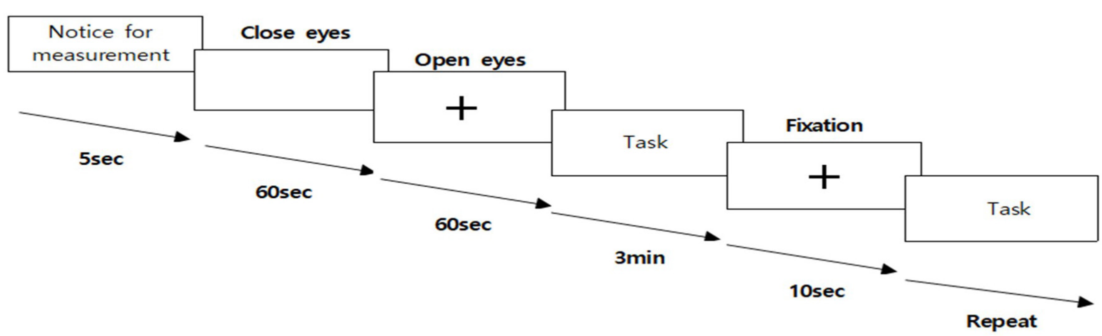

Fig. 2. Task paradigm for spatial ability task

Data Analysis

To analyze the brain activation areas of children's spatial ability, data collected through fNIRS measurement were preprocessed and analyzed using NIRSIT_Analysis Tool_v3.7.5 and MATLAB software (R2022b). After performing Marker work for each subject on Raw data, pre-processing was executed through high-pass filter, low-pass filter, and baseline setting to remove noise during measurement. Modified Beer-Lambert Law(MBLL) was applied to convert the optical signals of each wavelength into Oxy-Hb and Deoxy-Hb. In particular, Oxy-Hb has a higher signal-to-noise ratio and is more sensitive to changes in brain oxygenation (Lindenberger, 2009). Therefore, in this study, Oxy-Hb was used as an index to analyze the blood oxygen concentration. The concentrations of Oxy-Hb and Deoxy-Hb were analyzed during spatial task execution using the generalized linear model (GLM) method. In the individual level analysis, the activation beta coefficients for each channel were extracted. In group GLM, thermodynamic signals were extracted from channels showing significant activation by combining beta coefficients of all participants. The calculated β value for each channel was derived by executing a single sample t-test for each spatial ability component and by gender. In order to see the gender difference, a significant channel was derived by executing an independent sample t-test using the β values for each channel of the boy and girl groups. Finally, BrainNet Viewer v1.7 was used to visualize the brain anatomical location and activation of significant channels.

Results and Discussion

Brain Activation Region Analysis for Component of Spatial Ability

To analyze which brain regions children activate to solve spatial tasks, the blood oxyhemoglobin (Oxy-Hb) concentration was statistically analyzed for component of spatial ability (see Fig. 3, Table 1).

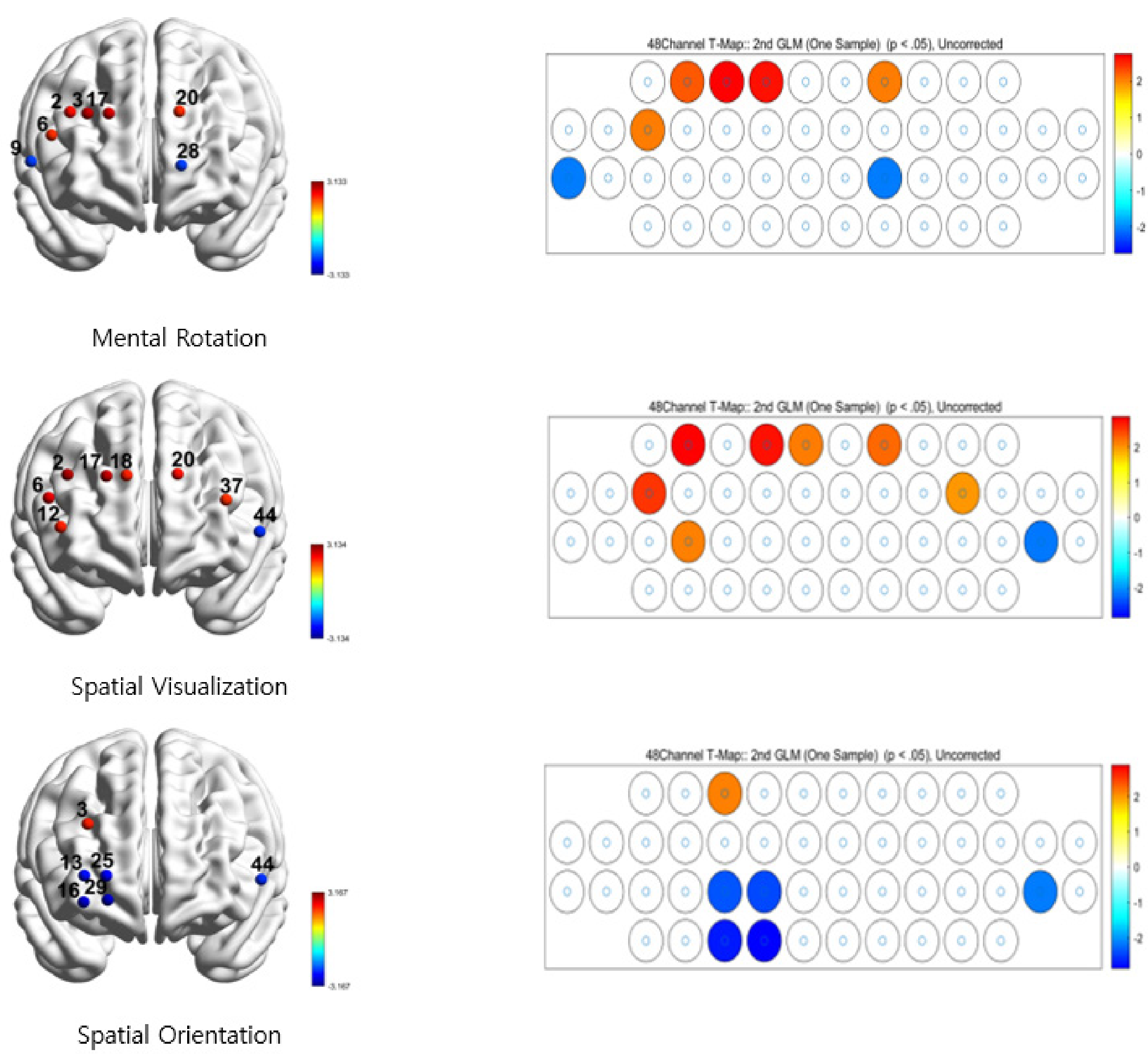

Fig. 3. Brain activation channels by component of spatial ability

Results of analysis of brain activation regions for component of children's spatial ability, in the Oxy-Hb concentration was significantly high in channels 2, 3, 6, 17, and 20 of the DLPFC (Dorsolateral Prefrontal Cortex), was significantly lower in channel 9 of the VLPFC (Ventrolateral Prefrontal Cortex) and channel 28 of the FPPFC (Frontopolar Prefrontal Cortex) during mental rotation. In spatial visualization, in the Oxy-Hb concentrations were significantly high in channels 2, 6, 17, 20, and 12 and 37 of the DLPFC, and significantly lower in channel 44 of the VLPFC. In spatial orientation, in the Oxy-Hb concentration was observed significantly higher in channel 3 of the DLPFC, and significantly lower in channels 44, 25, and the OFC (Orbofrontal Cortex). In all components of spatial ability, the DLPFC and FPPFC were activated significantly higher, and the VLPFC was activated significantly lower. And the OFC was observed only in spatial orientation, and all four brain regions showed significantly lower activation.

Table 1. GLM analysis results for component of spatial ability

	Region	BA	Channel	Hemisphere	t	*p*
Mental Rotation	DLPFC	9	2	R	2.265	.027
			3	R	2.736	.008
		46	6	R	2.079	.042
		10	17	R	2.643	.011
			20	L	2.064	.043
	VLPFC	45	9	R	-2.081	.042
	FPPFC	10	28	L	-2.065	.043
Spatial Visualization	DLPFC	9	2	R	2.849	.006
		46	6	R	2.550	.013
		10	17	R	2.761	.007
			20	L	2.260	.027
	VLPFC	47	44	L	-2.187	.033
	FPPFC	10	12	R	2.131	.037
			37	L	2.007	.049
Spatial Orientation	DLPFC	9	3	R	2.156	.035
	VLPFC	47	44	L	-2.178	.034
	FPPFC	10	13	R	-2.411	.019
			25	R	-2.481	.016
	OFC	10	16	R	-2.739	.008
			29	R	-2.880	.005

Among spatial ability components, mental rotation and spatial visualization showed a number of significantly higher activation channels of the DLPFC and were distributed over a relatively large area. The DLPFC is a key region for spatial attention, retention and memory of information. The DLPFC is related to the execution of spatial working memory tasks that remember the location of an object, and the right DLPFC is activated when manipulating working memory for visual information (Murphy et al., 1998). It is also positively correlated with uncertainty as the cortex involved in uncertainty (McLaughlin et al., 2009). There was less activation of the left parietal cortex when adults with better visuospatial skills used strategies (Reichle et al., 2000), and in solving the spatial rotation problem, adults with low ability showed greater activity in the right parietal cortex while executing spatial comparison tasks (Lamm et al., 1999). Similar to the results of previous studies, the average of correct answers to the components of children's spatial ability was the lowest in mental rotation (M=1.288). This is inferred that as the spatial task is difficult and the uncertainty increases, more neural resources are secured to solve it and channels of the DLPFC are significantly activated in the process.

In mental rotation and spatial visualization, the activation channels of the DLPFC, which are responsible for executive function and are involved in strategic processing, were very similar and were the same as BA 9, BA 46, and BA 10. It is presumed that similar brain regions are activated because children look at the movement of objects that have changed based on their own egocentric reference frame in order to solve a task.

In all components of spatial ability, the Oxy-Hb concentration in the VLPFC was significantly low. Significantly lower activity was seen in channel 9 (BA 45) of the VLPFC for mental rotation, and channel 44 (BA 47) of the VLPFC for spatial visualization and spatial orientation. The VLPFC has been hypothesized to mediate verbal working memory storage (Rypma & Esposito, 2000), and both BA 45 and BA 47 are related to Broca's area, which is responsible for language production. In order to successfully solve spatial tasks, child must be able to understand and analyze objects, images, and spatial relationships, and especially solving unfamiliar problems seems to require more spatial ability. Thus, the low brain activity of the BA 45, BA47 which is related to Broca's area of the VLPFC, is interpreted as a result of deactivation and inhibition the language related part and focusing more cognitive processing on solving nonverbal spatial tasks.

Spatial visualization is the ability to imagine images and mentally transform them to reconstruct spatial forms (Kang, 2023), and the concentration of Oxy-Hb in the FPPFC was significantly higher. The FPPFC is also activated when deciding when to shift attention from external information, such as perceptual stimuli, to internal information in working memory (Burgess et al., 2007). Spatial visualization requires a relatively multistep complex manipulation and transformation process that requires structural imagination to find the positional suitability of each part through the perceptual features of the figure, which is an external stimulus. Therefore, it is inferred that the FPPFC is activated while retrieving information from working memory and simultaneously thinking about where and how should be placed shapes of what size and shape.

On the other hand, spatial orientation showed relatively more channels with significantly lower activation. Low activation is interpreted as requiring less cognitive processing due to reduced dependence on cognitive effort and attention to solve the task. Artemenko et al., (2018) reported that frontal lobe activation decreased when children made less effortful calculations in the subtraction task, which was similar to the results of this study. The average of spatial orientation (M=1.627) was relatively the highest. The first and second grades of elementary school are the time when children transition from the pre operational stage to the concrete operational stage, and children can use both egocentric and allocentric perspectives. They use an allocentric perspective more reliably and spontaneously in spatial orienting. Therefore, it seems that the task was solved with relatively less effort, resulting in less activation.

In particular, only spatial orientation showed significantly lower activation in the OFC. The OFC plays a central role in emotional signaling. It processes information related to desire, motivation, and regulates various emotional, affective behaviors and information to suit the situation, and performs appropriate social behavior (Stalnaker et al., 2015). This can be evidence to support that spatial orientation is solving tasks based on an allocentric reference frame. Moreover, low activation in the OFC is interpreted as being involved in children inhibiting emotional and affective triggers and imagining or inferring the outcome of a spatial orientation task.

Brain Activation Region of Spatial Ability by Gender

Behavior Results for Component of Spatial Ability by Gender

To analyze whether there was a gender difference in children's spatial ability, an independent samples t-test was conducted for each component, and the results are shown in Table 2.

Table 2. Difference test for component of spatial ability by gender

	Mental Rotation				Spatial Visualization				Spatial Orientation			
	M	SD	t	*p*	M	SD	t	*p*	M	SD	t	*p*
Boys	1.467	1.105	.925	.359	1.300	.915	-1.260	.213	1.433	1.104	-1.538	.129
Girls	1.103	1.012			1.586	.824			1.827	1.197		

There was no significant difference in children's spatial ability in the components mental rotation, spatial visualization, and spatial orientation by gender. However, among spatial abilities, boys had the highest mean (M=1.467) in mental rotation, and girls had the highest mean (M=1.827) in spatial orientation. Mental rotation is the ability to imagine what a two-dimensional or three-dimensional object would look like when rotated about one axis or one point, and is the ability to mentally judge the result of rotation for the entire shape of the object (Kang, 2023). This is consistent with a study showing that there was no significant difference between genders in solving the mental rotation task in children in the second grade of elementary school (Neuburger et al., 2011), and that there was no gender difference in the photo rotation test in 4-6 year old preschool children (Quaiser-Pohl, 2003) is contextually similar. This is inferred because female students are often exposed to concrete objects such as blocks, dominoes, and cubes in educational and environmental aspects where they can have diverse experiences with today's space. However, different research results (Linn & Peterson, 1985; Titze et al., 2010) have been presented on whether there are significant gender differences in mental rotation, and no consensus has yet been reached. Therefore, it is necessary to conduct systematic research on various variables such as task complexity, strategy use, and working memory to determine whether gender differences occur and their causes.

Girls had the highest average in spatial orientation. This is consistent with research results showing that spatial orientation scores were higher than mental rotation and spatial visualization in previous studies targeting elementary school students (Fowler et al., 2022; Kang, 2023; Ramful et al., 2017). There was no significant gender difference in spatial orientation in children aged 4-8 years (Frick et al., 2014), and in children aged 3-6 years, girls performed better than boys, but there was no significant difference in gender (Nardini et al., 2006). Spatial orientation is the ability to accurately predict changes in the direction of an object and to understand and manipulate relationships between different positions in space. This means that girls use the other-centered frame more efficiently than boys. Merrill et al., (2016) reported that gender differences did not change significantly in the wayfinding task of children aged 6 to 12 years, and while girls used verbal memory a lot to find landmarks, boys preferred psychometric spatial ability. This allows us to infer that boys and girls use different cognitive strategies and tend to process information in the process of solving spatial orientation. Therefore, there is a need to conduct specific research using various variables on the strategies used when solving children's spatial orientation tasks.

Brain Activation of Spatial Ability in Boys and Girls

The Oxy-Hb concentration of boys and girls was statistically analyzed to determine which brain regions are activated to solve spatial tasks (see Fig. 4, Table 3).

As a result of analyzing the significant activation channels for each brain region shown in the boys' spatial task execution, the Oxy-Hb concentration in channels 3, 6, 17, 18, and 20 of the DLPFC and channels 12 and 36 of the FPPFC were found to be significantly high. Girls showed significantly lower concentrations of Oxy-Hb only in channel 44 of the VLPFC. That is, boys had significantly higher activation in many channels of the DLPFC and FPPFC, while girls had significantly lower activation in only one channel of the VLPFC.

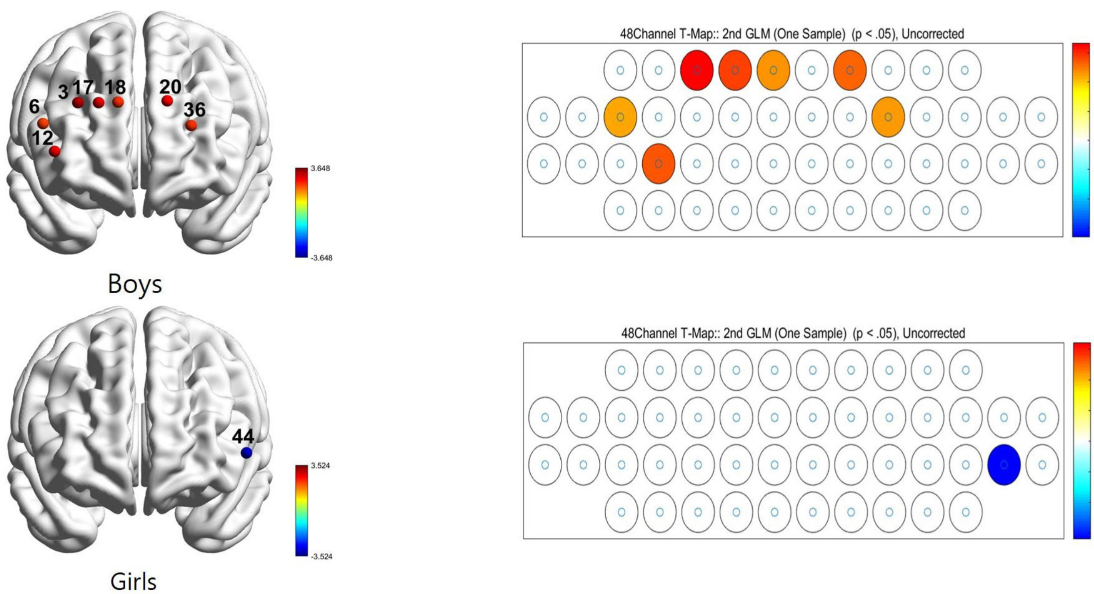

Fig. 4. Channels with significant differences in brain activation of spatial ability in boys and girls

Boys showed significantly higher activation of the DLPFC and FPPFC to solve spatial tasks. The DLPFC is responsible for attention and memory maintenance, and is involved in strategic processing, which is a high-level executive processing process, monitoring and manipulating externally generated information, or coordinating dual tasks (Toepper et al., 2010). For the successful execution of spatial tasks, boys must mentally rotate shapes and match them to the target task. And in order to construct the entire image by combining the parts of the figure, the length and angle of the side must be mentally transformed. During this cognitive processing, there appears to be more activation of the DLPFC to focus attention, manipulate new information, and execute necessary strategies. The FPPFC is involved in memory recall, adaptive decision making, and learning location relationships (Milovanovic et al, 2020). The activation of the FPPFC was relatively high in the group with the highest ability in solving child's transformation geometry tasks (Kang, 2020). It seems that children remember the perceptual characteristics of shapes to solve spatial tasks, recognize the relationship between figures, seek new alternatives through reasoning, and show high activation of the FPPFC for better decision making.

Table 3. GLM analysis results of spatial ability in boys and girls

Gender	Region	BA	Channel	Hemisphere	t	*p*
Boys	DLPFC	9	3	R	3.316	.002
		46	6	R	2.240	.033
		10	17	R	2.898	.007
			18	R	2.366	.025
			20	L	2.673	.012
	FPPFC	10	12	R	2.782	.009
			36	L	2.319	.027
Girls	VLPFC	47	44	L	-3.204	.003

On the other hand, girls showed significantly lower activation only in channel 44 of the VLPFC in executing spatial tasks. Channel 44 is an area corresponding to BA 47, which plays a central role in the prefrontal language production system and is involved in identifying the meaning of words and sentences (Ardila et al., 2017). It suggests that girls try to solve the task by deactivating less necessary linguistic parts rather than activating various brain regions to solve the spatial task. This means that girls use partial strategies to solve spatial tasks, control activity only in the areas they need. Through this, it is inferred to execute tasks while increasing brain efficiency.

Brain Activation differences of Spatial Ability between Gender

The difference in the Oxy-Hb concentration between boys and girls was analyzed using an independent samples t-test to analyze which brain regions are activated in solving spatial tasks (see Fig. 5, Table 4).

As a result of significant activation channel analysis by brain area in executing spatial tasks between genders, in the Oxy-Hb concentration was observed significantly higherin channel 17 of the DLPFC, channel 36 of the FPPFC, and channel 44 of the VLPFC in boys than in girls.

Fig. 5. Channels with significant differences in brain activation of spatial ability between gender

Boys seem to solve spatial tasks by activating more diverse brain regions than girls. Spatial ability is related to the visual processing of the brain. DLPFC is a key area related to the location, shape, order of space and is involved in decision making and control work (Cieslik et al., 2013). The VLPFC is involved in visual memory comparison to judge new information, maintenance or rehearsal of working memory contents, and is active when information is maintained (McLaughlin et al., 2009). And the FPPFC can regulate the DLPFC and VLPFC to achieve task goals or maximize task execution, and can evaluate internally generated information (Braver & Bongiolatti, 2002).

Table 4. GLM analysis results of spatial ability between gender

Region	BA	Channel	Hemisphere	t	*p*
DLPFC	10	17	R	2.206	.048
FPPFC	47	36	R	2.396	.037
VLPFC	47	44	L	2.854	.006

It is seemed that boys activate the DLPFC to identify the location of objects in space and produce a variety of strategies, and the VLPFC to mentally transform shapes and maintain and compare them to solve the spatial tasks. And it is inferred that FPPFC, which has a high level integrated function to make correct decisions through evaluation, has been activated. The FPPFC is also involved in controlling and managing moral judgments and impulses (Yamuro et al., 2016). In other words, it seems that the FPPFC activity was high to control distractions and inhibit irrelevant information to solve spatial tasks.

Conclusions and Implications

This study was analyzed using fNIRS to find out which brain regions were activated in elementary school students (1st-2nd) to solve spatial tasks, and the conclusions are as follows.

First, in mental rotation, spatial visualization, and spatial orientation, the DLPFC was activated significantly highly in a relatively many channels, and the VLPFC was activated significantly lower. This means that the DLPFC is specialized in spatial working memory and also plays an important role in high-level executive processes. And, there was significantly lower activation in VLPFC, which corresponds to BA 45 and BA 47, Broca's area, which is responsible for language production. This shows that the child is focusing on execution to solve the spatial task, strategically processing it using visual information, and focusing more neural resources on the non verbal parts by inhibiting the language related parts.

Second, spatial orienting showed significantly lower activation in brain regions, and the average of correct answers was relatively highest. As the difficulty of the task decreased, activation in brain regions identified as mediating spatial cognitive processing decreased. This indicates a reduced reliance on cognitive effort and attention. Better neural efficiency was associated with less brain activity, suggesting that spatial ability is related to capacity limitations of working memory and allocation of available central executive resources. Furthermore, it suggests an inverse relationship between spatial task difficulty and neural activity, and brain activation intensity provides insight into the level of mental effort, that is, how hard child thought to solve the task.

Third, the activation channels of the DLPFC, which are responsible for executive function and are involved in strategic processing, were very similar in mental rotation and spatial visualization. Activation of the OFC, which is involved in processing information related to desire or emotion, was observed only in spatial orientation. This supports the finding that children use an egocentric frame to execute mental rotation and spatial visualization tasks, and an allocentric frame for spatial orientation (Fernandez-Baizana et al., 2021) to solve the task.

Fourth, There was no significant difference in children's spatial ability in the components mental rotation, spatial visualization, and spatial orientation according to gender. This is Vbecause today's young children, even female students, can often experience various objects related to space in educational settings. And boys had the relatively highest average in mental rotation. This is a result of the boy's use of an overall strategy of rotating the entire object, and this is also seen in the neuroimaging data mentioned later. Girls had the highest average in spatial orientation. The girls seems to have solved the task by using language memory as well as allocentric frame. The reason for this was that it was possible to know the use of allocentric frame through OFC activation in neural image data, and it was found that language memory was used when solving tasks by inhibiting the activation of the language part.

Fifth, boys activated relatively many channels significantly higher in the DLPFC and FPPFC to solve spatial tasks, and girls activated only one channel significantly lower in the VLPFC. In other words, boys solved tasks by activating many channels in the brain region, while girls deactivated channels and used neural resources efficiently.

Sixth, boys showed significantly higher activation than girls in the DLPFC, VLPFC, and FPPFC, in terms of gender differences in brain activation areas. In particular, the FPPFC was activated while supervising or integrating cognitive processing during the task was being executed. In this way, the use of various brain regions in boys means the possibility of using more diverse strategies and seeking alternatives when solving new types of spatial tasks that are difficult or unfamiliar. Furthermore, this study provides neuroimaging data for the result that boys use holistic strategies and girls use piecemeal strategies to solve spatial tasks.

Based on the above conclusions, the educational implications are as follows. First, while boys activated various brain regions to solve spatial tasks, girls deactivated language related regions. Therefore, it suggests that spatial learning through activities that understand and directly manipulate spatial characteristics of objects may be more efficient than understanding meaning through language to improve a girl's spatial ability. Second, spatial orientation was recognized relatively easily by children. Therefore, it suggests that it is necessary to organize various educational activities related to mental rotation and spatial visualization in the elementary mathematics curriculum. Third, this study had age limitations as it targets first and second grade elementary school students. There is a need to examine the development process of spatial abilities, changes in brain activation regions in students of various ages through cross sectional or longitudinal studies. This will be able to provide visual data that can directly confirm the child's cognitive development process.

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