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DETERMINING THE ROLE OF SPATIAL ABILITY IN PERFORMING LUNAR PHASE CHANGE TASK USING BRAIN ACTIVITY ANALYSIS

Naeun Lee,
Ilho Yang,
Seongun Kim

Abstract. *Many students have difficulty understanding the concept of lunar phase changes (LPCs) due to spatial ability problems such as perspective-taking (PT) and mental rotation (MR). Therefore, this study aimed to compare brain activity during PT and MR tasks while performing the LPC task to determine the involvement of PT and MR. This study measured brain waves using EEG in 20 participants while solving the 3 tasks. First, the power values in the theta band of all cortical areas showed a significant difference between MR and LPC tasks. Second, in the strategy execution section with a statistically significant difference, the occipital lobe and limbic system were mainly active during the PT task, whereas the frontal lobe was mainly active during the LPC task. Third, for strategy execution, during MR and LPC tasks, the frontal lobe, temporal lobe, and limbic system were all activated to significantly different degrees. Therefore, both PT and MR, particularly PT, are required to solve the LPC task. Moreover, for students who have difficulty learning LPC, it is necessary to recognize the need for spatial ability, such as PT ability, and establish an appropriate teaching strategy.*
Keywords: *brain activation, electroencephalography, lunar phase change, mental rotation, perspective-taking*

Naeun Lee, Ilho Yang, Seongun Kim
Korea National University of Education, South Korea

Introduction

Research Context

Although lunar phases are a natural phenomenon that is commonly encountered in daily life, most students have difficulty understanding the concept of lunar phase changes (LPCs) (Plummer, 2014; Subramaniam & Padalkar, 2009; Trundle et al., 2007). Prior studies have reported that students experience difficulty understanding LPCs because of the following two reasons. The first reason is misconceptions among students. Trundle et al. (2007) reported that students have difficulty understanding LPCs due to alternative concepts, such as that the lunar phase is caused by the earth's shadow. Kavanagh et al. (2005) revealed that these misconceptions among students regarding lunar phases persist until their adulthood. The second reason is differences in students' cognitive abilities. Studies assessing cognitive abilities mainly focus on spatial ability. This is because understanding various aspects of astronomy depends on an individual's ability to explain the observed phenomena and predict future observations using the actual movements and relative positions of celestial bodies, which require spatial abilities (Cole et al., 2015; Plummer et al., 2011).

The spatial abilities that are considered to be associated with the understanding of LPCs include perspective-taking (PT) and mental rotation (MR) (Black, 2005; Bower, 2017; Gali & Venukapalli, 2021; Plummer et al., 2022). PT is defined as the ability to mentally perceive another individual's perspective, inferring their internal states, such as what they are observing, as well as knowledge states and preferences based on visual experiences (Moll & Tomasello, 2006). In contrast, MR is defined as the ability to rapidly and accurately rotate two- or three-dimensional images mentally (Linn & Peterson, 1985).

Previous studies on students' understanding of LPCs from the perspective of spatial ability have focused on spatial ability tests and science concept tests and calculated the correlation between the two test scores (Bower, 2017; Gali & Venukapalli, 2021; Wilhelm et al., 2017) or analyzed the results

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of student interviews (Plummer et al., 2022; Wilhelm et al., 2022). However, in these studies, it is difficult to identify students' cognitive processes during the problem-solving process. Moreover, there is a lack of empirical research that demonstrates the moment at which spatial ability is used during the problem-solving process and reveals that spatial ability is required to solve problems. Therefore, it is necessary to explain how learners select strategies and overcome challenges while solving LPC tasks based on specific evidence in a chronological order. Furthermore, considering the fact that both PT and MR are necessary for understanding LPCs, the approach for teaching LPC concepts should be discussed by determining whether these two spatial abilities are associated with LPCs and, if so, which one of them is more closely associated.

Research Focus

Based on the abovementioned necessity, this study used electroencephalography (EEG), a neuroscience-based technique, to collect and analyze quantitative and empirical brain activity data while solving tasks associated with PT ability, MR ability, and LPC. The cognitive processes identified through psychological research rely on subjective data-driven inferences, which have limitations in providing objective and empirical data (Turner et al., 2017). Therefore, many researchers argue that neuroscientific research should be conducted to overcome the limitations of cognitive psychological research in education and improve the understanding of aspects of human learning and performance (Koizumi, 2004; Posner & Rothbart, 2005).

Research Aim and Research Questions

This study measured the brain activities while solving tasks related to PT ability and MR ability. Based on these results, brain activities were analyzed while solving a task associated with LPCs. Thus, this study aimed to empirically reveal how the concepts of LPC, PT ability, and MR ability are related to each other. The research questions guiding this study were as follows:

1. What differences in brain waves arise when solving LPC tasks in comparison to PT and MR tasks?
2. What differences exist in the activated brain regions when solving LPC tasks as opposed to PT and MR tasks?

Research Methodology

Background

This study used a neuroscience-based method, EEG, to collect and analyze quantitative and empirical brain activity data while solving spatial ability tasks and LPC tasks. EEG demonstrates excellent time resolution, which enables precise tracking of changes in brain activity for up to 1 ms (Wendel et al., 2009). Advancements in EEG technology have also improved spatial resolution, making it suitable for neuroimaging analysis (McLoughlin et al., 2013). Recent studies have shown that EEG can be used to measure and analyze brain activity while solving various tasks, thereby extending its application beyond scientific tasks (Scheer et al., 2018; Zhu et al., 2021). Before conducting this research, the method of performing the task and overall measurement process were explained to the research participants in detail. In particular, precautions related to EEG measurements, such as minimizing movement during the measurement process, were emphasized. EEG was measured when the research participants performed the spatial ability and LPC tasks, and the differences in the relative power spectrum and activated brain regions for each task were analyzed. The period for collecting data from research participants was from September to November, 2022.

Participants

The study participants were 20 male college students (average age, 22.1 years) attending a university in the central region of South Korea. This study recruited adults instead of children and adolescents because brainwave patterns can significantly vary with age and developmental stages during childhood and adolescence, limiting the achievement of consistent results (Matsuura et al., 1985). In addition, previous research on spatial abilities has shown sex-dependent differences, which are also evident in the observed brain activity patterns (Geiser et al., 2006;

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Maeda & Yoon, 2013; Robert & Bell, 2000). Thus, only male students were recruited in this study. Furthermore, to minimize factors that could influence EEG measurements, individuals who were right-handed, had normal vision in both eyes, and had no physical illnesses, mental health history, claustrophobia, or metallic objects in their bodies were included. The number of study participants was determined based on the characteristics of the task, availability of EEG equipment, and duration of the study. It was estimated that 20 participants would be adequate to obtain statistically significant results because the research design was rigorous, based on discussions with science education experts with former EEG experience and EEG measurement experts. Zhu et al. (2021) also analyzed brain activity while solving scientific tasks and revealed statistically significant results in a small group of study participants. This study was approved by the Institutional Review Board of Korea National University of Education, and informed consent was obtained from all participants after receiving a sufficient explanation of the research process.

Development of Spatial Ability Task

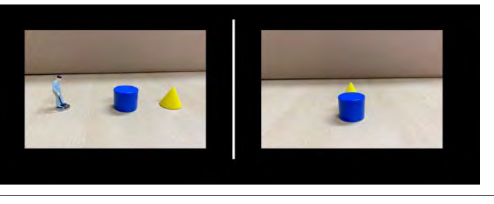
Considering that the participants were university students, a new assessment tool was developed for PT measurements based on the assessment tool used by Frick et al. (2014), which measured PT abilities of children aged 4–8 years. This tool emphasized the visual representation of verbal expression, enabling participants to easily understand the intent of the questions and respond rapidly. Specific descriptions of PT test questions are presented in Table 1A.

Representative tests for measuring MR ability include the Purdue Spatial Visualization Test; Rotation (PSVT:R) (Guay, 1976), and the Kit of Factor-Referenced Cognitive Tests (Ekstrom, 1976). Initial measurements using PSVT:R showed large variations in the time required to solve each question. Therefore, measurements obtained from the Kit of Factor-Referenced Cognitive Tests were used to ensure more consistent problem-solving times. Specific descriptions of MR test questions are presented in Table 1B.

Development of the LPC Task

This study aimed to determine, from a neuroscientific perspective, how brain activity is related to spatial abilities such as PT and MR abilities while solving LPC tasks. Therefore, to minimize the activation of different thought processes while solving LPC tasks, the tasks were developed in a question format that provided minimal information. LPCs are covered in the sixth grade of the South Korean science curriculum. Science textbooks describe activities involving the observation of changes in the Moon's shape over several days to recognize periodic changes in its shape and position. Questions for the LPC concept test were developed based on a commonly used LPC concept test questionnaire (Cid & Lopez, 2010; Meyer et al., 2011; Wilhelm et al., 2017), known as the Lunar Phase Concept Inventory (Lindell & Olsen, 2002). The drafted tasks were validated by three earth science education experts. Based on their corrections, the sun was revised to parallel rays of sunlight, and the lunar phase pattern presented in the example was verified to ensure that there were no errors. Additionally, experts' opinions suggested that the orbits of the Sun and Moon were greatly distorted during the question development process. However, to implement the EEG task paradigm, images of the Sun, Earth, and Moon were constructed, which differed from their actual sizes and distances between them, which were explained to the participants in advance. A total of 16 questions were newly developed and validated through discussion in five regular seminars attended by three science education experts. Specific descriptions and examples of task questions are presented in Table 1C.

Table 1
Examples of Spatial Ability and Lunar Phase Change Tasks

Task Name	Question Description	Question Example	Number of Questions
A. Perspective-taking ability	Determine whether the view of the shapes in the left picture matches that in the right picture from the person's perspective		16

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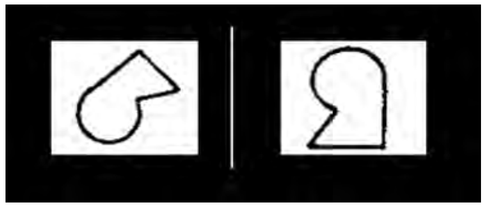
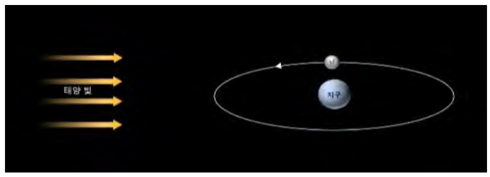
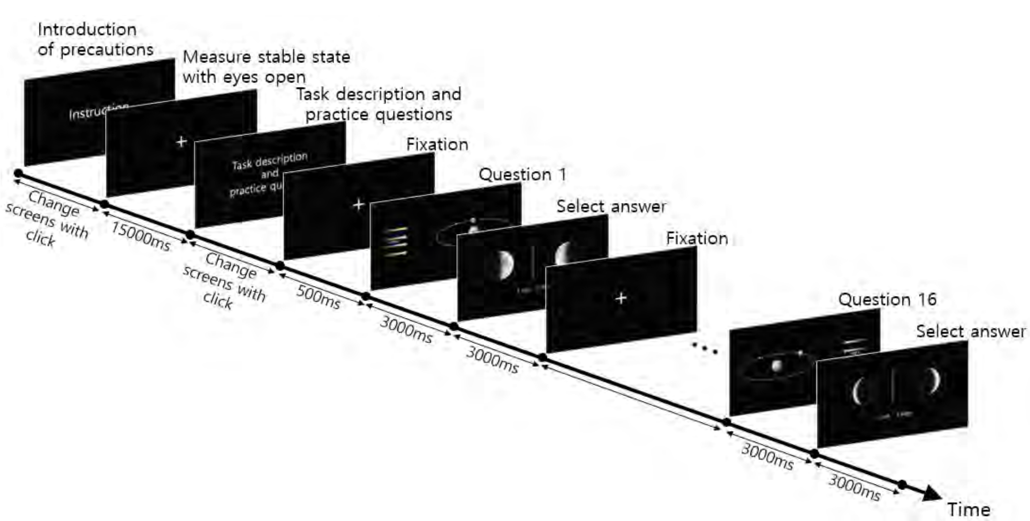
Task Name	Question Description	Question Example	Number of Questions
B. Mental rotation ability	Determine whether the two shapes are identical		16
C. Lunar phase change	Determine the lunar phase visible from the Earth, based on the positions of the Sun, Earth, and Moon in space		16

Task Design

The EEG measurement paradigm included PT, MR, and LPC tasks performed using E-prime software. Before each task, resting-state EEG was measured with eyes of the participants open. The baseline EEG measurement was obtained as per the following instructions. First, a brief attention guideline was provided, followed by the measurement of EEG in an eyes-open and stable state. The measurement involved focusing on a "+" symbol displayed on the screen for 15 s, which was repeated thrice. The task paradigm included providing instructions for EEG measurement, describing the tasks, and asking three practice questions, followed by the display of task instructions and 16 main questions. Following the advice of an eye-tracking research expert, a "+" sign was displayed for 500 ms immediately before displaying the question regarding fixing the eyes on the screen. Interference with EEG signals caused by muscle movement while pushing the buttons was detected through preliminary tests, and question presentation and response selection screens were separated to prevent the interference. The question and response selection screens were displayed for 3000 ms, accounting for the participants' previously measured response times. Any additional descriptions or instructions were presented on the screen until the participant pressed a key to proceed onto the next screen. The total time required for completing each task was approximately 3 min; a 2-min rest period was allowed between the tasks to reduce brain fatigue. The participants solved practice tasks before the actual measurements to ensure their understanding of the task procedure. The specific task paradigms are shown in Figure 1.

Figure 1
Task Paradigm for the LPC Task



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Measurement Procedures

EEG measurements were conducted in a shielded room with blocked external noise and consistent lighting conditions. A 64-channel HydroCel Geodesic Sensor Net (Electrical Geodesics, Eugene, Oregon, USA) was used for EEG measurements, with a sampling rate of 1,000 Hz, high-pass filter of 0.1 Hz, low-pass filter of 70 Hz, and notch filter of 60 Hz. Net Amps 400 amplifier (Electrical Geodesics, Eugene, Oregon, USA) and Net Station 5 software (Electrical Geodesics, Eugene, Oregon, USA) were used for EEG data collection.

The participants were instructed to minimize movement during EEG measurements. To reduce impedance between the scalp and electrodes, the participant's hair was wetted with water and their heads previously fitted with an EEG net were immersed in a potassium solution. Subsequently, the participants entered the shielded room, where electrode impedance was assessed using Net Station Acquisition software to ensure appropriate EEG data collection. Tasks were displayed on a monitor within the shielded room; the researcher monitored the tasks from outside the room to ensure appropriate presentation and EEG data collection. The EEG measurement process lasted for approximately 1 min for obtaining resting-state EEG in eyes-open state and approximately 3 min for task completion, with a 2-min rest period between the tasks to reduce fatigue. The total time for EEG measurement in all tasks was approximately 15 min.

Figure 2
Geodesic EEG System

Data Analysis

To analyze differences in brain activity, EEG data were preprocessed. First, the frequency range of the data was set to 1–50 Hz using Net Station Tools software, and channels with severe artifacts were removed and corrected. In addition, independent component analysis was performed to remove artifacts resulting from factors such as eye blinks and muscle activity. Recording units (epochs) were created by dividing each question, and defective channels were detected. Epochs with >10 channels marked as defective by >10% of the entire problem-solving time were excluded from the analysis. After preprocessing, two methods were used for analysis: relative power spectrum difference analysis and comparison of brain activation areas using Brainstorm.

To compare brain activation while solving LPC task and PT and MR tasks, relative power spectrum difference analysis was employed. As individuals have varying brainwaves (Su et al., 2010), this analysis allows the comparison of task-related brain activation with that in the baseline state measured during resting. Herein, relative power values were calculated by dividing the power values of specific frequency bands by those across the entire frequency range (4–50 Hz). The frequency bands used in the analysis included theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–50 Hz), and brainwaves measured in μV were subjected to the fast Fourier transform method to calculate the power values in each frequency band. The relative power values obtained in this manner were then compared in each cortical region to determine changes in brain activity between the tasks. Accordingly, a one-way analysis of variance with the Scheffé post hoc test was used to analyze differences in relative power spectra between the tasks in each frequency band.

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Furthermore, while solving each task, the differences in brain activation areas were compared and analyzed using Brainstorm software, which allows visualization and analysis of EEG data and solves inverse problems (Tadel et al., 2011). The EEG data obtained while solving PT tasks and LPC tasks, as well as those obtained while solving MR tasks and LPC tasks, were compared. A paired-sample *t*-test (paired group, A = B) in the omega frequency band (4–50 Hz) was conducted. Significant differences in current density were noted at *p*-values of <.05, and the power values for each brain region during these time periods were averaged and extracted. The most activated brain region for each task was determined, and the significance of differences in brain activation between the two tasks was analyzed. Brain regions were identified using Mindboggle software provided by Brainstorm. This software divides the cerebral cortex into 62 regions, 31 per hemisphere, allowing accurate brain labeling and visualization (Klein et al., 2017).

Research Results

Relative Power Spectrum Analysis by Task Types

Theta Band Activation

The results of relative power spectrum analysis in the theta band are shown in Table 2. Significant differences were noted only between MR and LPC tasks in the frontal, parietal, temporal, and occipital lobe. Next, differences in theta band activity were observed in the frontal, parietal, temporal, and occipital lobe between LPC task and MR task, suggesting different spatial information processing and working memory activation during the LPC task.

Table 2
One-Way ANOVA with Scheffé Post Hoc Test for Theta Band Activation

Classification			*MD*	*SE*	*p*
Frontal lobe	A	B	−.035	.014	.049*
		C	.010	.014	.759
	B	A	.035	.014	.049*
		C	.045	.014	.008*
	C	A	−.010	.014	.759
		B	−.045	.014	.008*
Parietal lobe	A	B	−.025	.012	.112
		C	.005	.012	.906
	B	A	.025	.012	.112
		C	.031	.012	.043*
	C	A	−.005	.012	.906
		B	−.031	.012	.043*
Temporal lobe	A	B	−.030	.011	.032*
		C	−.002	.011	.990
	B	A	.030	.011	.032*
		C	.029	.011	.045*
	C	A	.002	.011	.990
		B	−.029	.011	.045*

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Occipital lobe	A	B	−.018	.012	.343
		C	.021	.012	.251
	B	A	.018	.012	.343
		C	.039	.012	.010*
	C	A	−.021	.012	.251
		B	−.039	.012	.010*

(A: Perspective-taking task, B: Mental rotation task, C: Lunar phase change task, * $p < .05$)

Beta Band Activation

The results of the relative power spectrum analysis in the beta band are shown in Table 3. In the beta band, significant differences were noted only between PT and the LPC tasks in the frontal lobe ($p < .05$).

Table 3
One-Way ANOVA with Scheffé Post Hoc Test for Beta Band Activation

Classification			*MD*	*SE*	*p*
Frontal lobe	A	B	.017	.012	.405
		C	.035	.012	.024*
	B	A	−.017	.012	.405
		C	.018	.012	.347
	C	A	−.035	.012	.024*
		B	−.018	.012	.347
Parietal lobe	A	B	.010	.013	.730
		C	.009	.013	.767
	B	A	−.010	.013	.730
		C	−.001	.013	.998
	C	A	−.009	.013	.767
		B	.001	.013	.998
Temporal lobe	A	B	.011	.012	.668
		C	.017	.012	.419
	B	A	−.011	.012	.668
		C	.005	.012	.912
	C	A	−.017	.012	.419
		B	−.005	.012	.912
Occipital lobe	A	B	−.006	.017	.936
		C	−.009	.017	.879
	B	A	.006	.017	.936
		C	−.003	.017	.989
	C	A	.009	.017	.879
		B	.003	.017	.989

(A: Perspective-taking task, B: Mental rotation task, C: Lunar phase change task, * $p < .05$)

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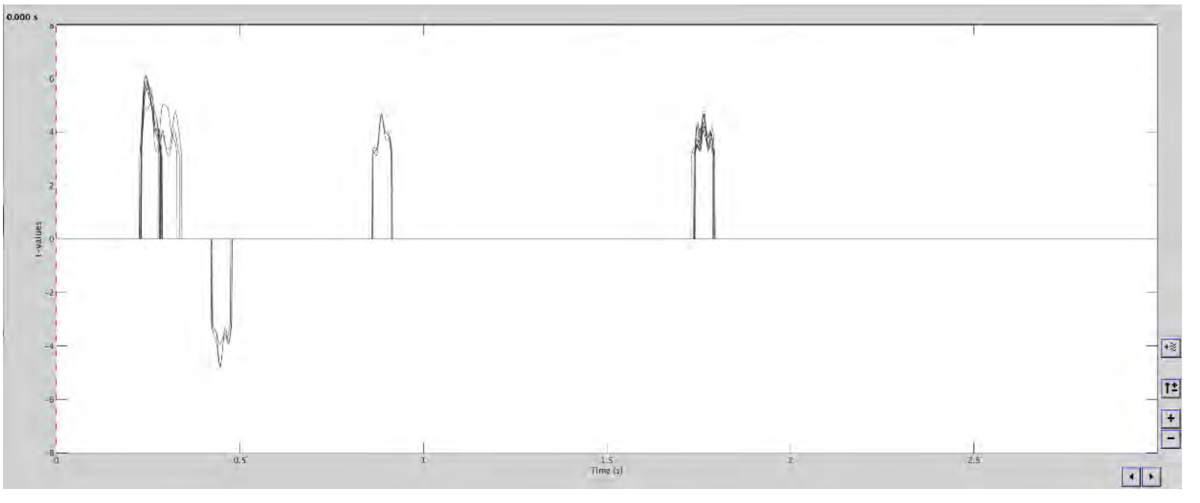
Brain Activation Analysis by Task Types

Differences in Brain Activation during PT and LPC Tasks

The differences in brain activity observed during PT and LPC tasks are presented in Figure 3 ($p < .05$). The output of nonparametric t-tests were t-value traces that were set to 0 at every channel and the time point at p-values of >0.05 (FDR-corrected). The time intervals indicated by these results and the task-specific prominent brain regions most activated during each time interval are detailed in Table 4.

Figure 3
Differences in Sensor Levels during PT and LPC Tasks



During the first time interval, compared with LPC task, a higher number of brain areas were activated while solving PT task, including the medial orbitofrontal cortex and paracentral lobule. In contrast, during LPC task, the most activated areas were parahippocampal and superior parietal regions. In the second, third, and fourth intervals, during PT task, the posterior cingulate cortex, lingual gyrus, and pericalcarine cortex, mainly located in the occipital lobe, were predominantly activated. In contrast, during LPC task, the medial orbitofrontal cortex, pars opercularis, and pars triangularis, mainly located in the prefrontal cortex, were activated.

Table 4
Brain Areas Highly Activated During Each Task for Each Time Interval with Differences in Brain Activity (PT Task vs. LPC Task)

Section	Time (ms)	Activated brain areas	
		Perspective-taking ability task	Lunar phase change task
1	227–341	Medial orbitofrontal Paracentral L	Parahippocampal superior parietal
2	422–478	Lingual L Posterior cingulate Entorhinal L	Medial orbitofrontal R Pars opercularis R Rostral anterior cingulate L
3	861–915	Pericalcarine Isthmus cingulate	Entorhinal Pars opercularis R
4	1730–1794	Isthmus cingulate L Paracentral L	Fusiform R Pars triangularis R

Differences in Brain Activation during MR and LPC Tasks

The differences ($p < .05$) in brain activity observed during MR and LPC tasks are illustrated in Figure 4. The significant time intervals indicated by these results are outlined in Table 5. The last 700 ms before the end of the

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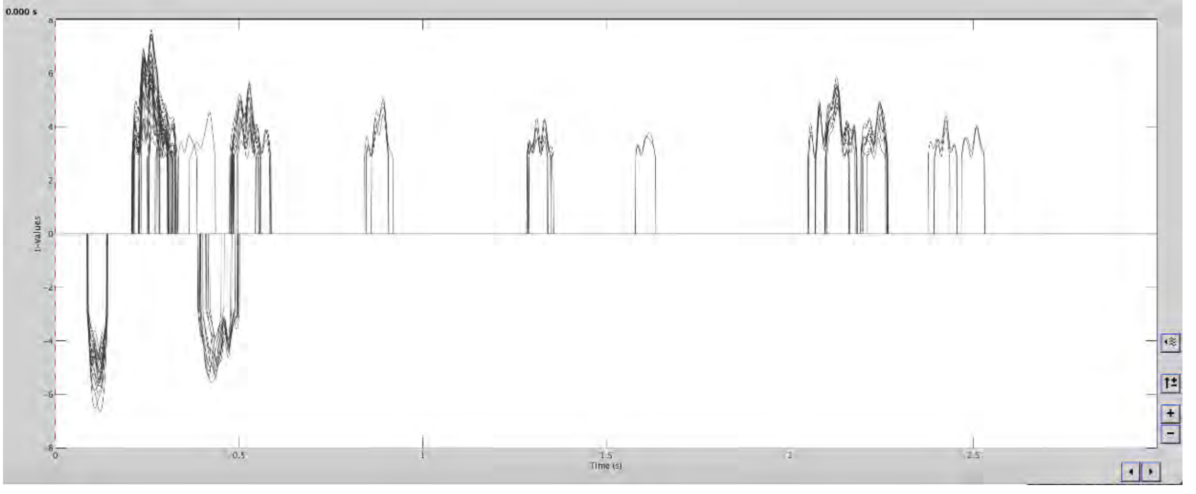
task presentation may reflect the preparation for pressing the button in the upcoming response screen (Gardony et al., 2017). Therefore, although significant differences in brain activity were observed, this time interval was excluded from the time interval analysis.

Figure 4
Differences in Sensor Levels during MR and LPC Tasks



During the first and second intervals, the brain regions that were more activated while solving MR task compared with those while solving LPC task were the precuneus, posterior cingulate cortex, fusiform gyrus, and pericalcarine cortex, indicating the influence of strategy selection.

From 400 ms after the task presentation until 700 ms before the end of the task presentation, six time intervals showed differences in brain activity between MR and LPC tasks. For MR task, during the early phase, the parahippocampal and entorhinal cortexes in the temporal lobe were activated, gradually transitioning to activation of frontal regions such as the medial orbitofrontal, lateral orbitofrontal, and posterior cingulate cortexes, associated with the prefrontal cortex and limbic system. In contrast, during LPC task, widespread activation was observed across various brain regions, including caudal anterior cingulate and isthmus cingulate cortexes in the limbic system; parahippocampal, fusiform, and lingual gyruses in the temporal lobes; and pars orbitalis and pars triangularis in the prefrontal cortex.

Table 5
Brain Areas Highly Activated During Each Task for Each Time Interval with Differences in Brain Activity (MR Task vs. LPC Task)

Interval	Time (ms)	Activated brain areas	
		Mental rotation ability task	Lunar phase change task
1	86–142	Precuneus Posterior cingulate L	Caudal anterior cingulate Rostral anterior cingulate R
2	208–387	Fusiform R Pericalcarine L	Entorhinal Superior parietal
3	388–501	Parahippocampal L Entorhinal L	Caudal anterior cingulate R Isthmus cingulate
4	502–587	Insula Medial orbitofrontal L	Parahippocampal R Pars orbitalis
5	841–919	Posterior cingulate Precuneus R	Rostral anterior cingulate L Fusiform R
6	1284–1356	Pars orbitalis L Isthmus cingulate	Insula L Lingual R

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Interval	Time (ms)	Activated brain areas	
		Mental rotation ability task	Lunar phase change task
7	1580–1634	Isthmus cingulate Lateral orbitofrontal R	Caudal anterior cingulate Pars triangularis R
8	2049–2267	Parahippocampal Paracentral	Superior temporal Pars triangularis

Discussion

Students encounter difficulty learning several scientific concepts. Assisting students to better understand these challenging scientific concepts is considered an important task in science education research. This is because systematic development of a child's cognitive system is one of the crucial aspects of education (Szucs & Goswami, 2007). LPCs are one of the scientific concepts that many students find difficult to understand (Plummer, 2014; Subramaniam & Padalkar, 2009). To effectively analyze the underlying causes of this difficulty and provide insights into specific neural structures that form the basis for complex cognitive processes, neuroscientific research is necessary (Geake & Cooper, 2003; Oliver, 2011). Therefore, this study analyzed the brain activation patterns while solving each task using EEG to elucidate the relationship between spatial abilities and the concept of LPCs, which had previously been studied using cognitive psychology methods (Black, 2005; Bower, 2017; Gali & Venukapalli, 2021; Plummer et al., 2022).

The theta band plays a role in processing spatial cues and integrating memory (Backus et al., 2016; Kober & Neuper, 2011), and a previous study suggested the importance of interactions mediated by theta oscillations between the hippocampus and prefrontal cortex in spatial memory (Zielinski et al., 2019). The parietal lobe is associated with spatial attention, spatial information processing, spatial working memory, and manipulation of working memory information (Curtis, 2006; Koenigs et al., 2009; Shafritz et al., 2002). The occipital lobe is associated with visual processing (Kurcyus et al., 2018), which impacts the theta amplitude (Miller et al., 2010). Thus, differences in occipital lobe brainwaves may indicate differences in image processing during MR and LPC tasks.

The beta band is associated with executive functions (Tschentscher & Hauk, 2016). Beta oscillations in the frontal lobe are inhibited when a participant imagines moving images (De Lange et al., 2008), but these oscillations are induced during memory maintenance and recall (Tallon-Baudry et al., 1999). In addition, the beta band is related to cognitive functions such as visual attention, perception, emotion, and working memory (Miller et al., 2018; Wang 2010). Therefore, differences in beta band activity in the frontal lobe suggest the involvement of different strategies and cognitive processes during LPC and PT tasks. Additionally, according to De Lange et al. (2008), beta waves in the frontal lobe are suppressed when imagining rotating images. Thus, compared with PT task, the lower beta values during MR and LPC tasks indicate more active imagination of rotating images.

According to previous studies, the time period within 400 ms after the presentation of a problem primarily reflects strategy selection, whereas that after 400 ms reflects its execution (El Yagoubi et al., 2003). Based on this, the differences in brain activation areas were first interpreted when performing PT and LPC tasks. According to a previous study, before 400 ms, the medial orbitofrontal cortex, which is a part of the prefrontal cortex, is associated with cognitive processes related to decision-making and expecting rewards when considering specific details (Rolls & Grabenhorst, 2008). The paracentral lobule includes a part of the supplementary motor area (SMA) associated with motor and sensory functions (Strotzer, 2009); a previous study revealed that the SMA is related to PT (Gunia et al., 2021). The parahippocampal region is linked to scene perception and spatial representation (Aminoff et al., 2013), whereas the superior parietal region is involved in spatial orientation, spatial location recognition, and working memory (Koenigs et al., 2009; Vandenberghe et al., 2001). Therefore, during the first time interval, the strategy selection process involving spatial reasoning was more active during PT task, whereas during LPC task, recognizing the scene, determining spatial locations, and using working memory were more relevant. After 400 ms, based on brain areas that differ in activity for each task, it was determined that the occipital lobe was mainly activated during PT task. In contrast, the prefrontal cortex was predominantly activated during LPC task. As the participant who solves the task continues to observe visual images, sustained activation occurs in the occipital lobe, whereas the cingulate cortex is known to be involved in learning and memory (Stanislav et al., 2013). The prefrontal cortex is

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activated during complex cognitive processes such as decision-making, inference, and learning (Collins & Koechlin, 2012). Thus, more complex cognitive processes are required for solving LPC tasks than for solving PT tasks.

Second, the differences in brain activation areas were interpreted when performing MR and LPC tasks. Before 400 ms, which reflected strategy selection, the brain regions that were more activated while solving MR task than while solving LPC task were the precuneus, posterior cingulate cortex, fusiform gyrus, and pericalcarine cortex, indicating the influence of strategy selection. The precuneus is associated with processing spatial and temporal images (Cavanna & Trimble, 2006) and is activated when solving spatial tasks such as PT (Kaiser et al., 2008; Vogeley et al., 2004). The posterior cingulate cortex, which is an essential component of the limbic system and is related to learning and memory (Stanislav et al., 2013), plays a role in motivating goal-directed behavior (Devinsky et al., 1995). The fusiform gyrus is primarily investigated in the context of face recognition (Kanwisher & Yovel, 2006; Saygin et al, 2012) but is also associated with recognizing visual words (McCandliss et al., 2003). Some parts of the fusiform along with the lingual gyrus are involved in perceiving and processing color (Allison et al., 1993). Thus, it may be connected to various neural pathways related to perception. Additionally, the pericalcarine region is a key area in the visual cortex related to visual processing (Huettel et al., 2004). Conversely, the brain regions that were more activated when solving the LPC task were the caudal anterior cingulate cortex, rostral anterior cingulate cortex, entorhinal cortex, and superior parietal lobule. The entorhinal cortex is a part of the temporal lobe and is considered fundamental for spatial exploration and spatial memory (Jacobs et al., 2010). Thus, during the first and second intervals, processes related to motivation, processing of visual images, and learning and memory occurred when solving the MR task. In contrast, when solving LPC task, which required spatial reasoning and utilization of working memory based on given visual information, participants engaged in processes that involved representing and processing of spatial images. After 400 ms, although some regions, such as the caudal anterior cingulate cortex, parahippocampal gyrus, and pars orbitalis, were activated during both tasks, the distinct timing of their prominent activation suggests that different cognitive processes occur during the execution of strategies in the two tasks.

Figures 3 and 4 indicate that compared with LPC task, brain activity exhibited differences in a higher number of time intervals during MR task. This suggests that when solving the LPC task, brain activity was more similar to that observed in the comparison of MR and PT tasks, indicating that the cognitive processes involved in LPC task are closer to those of PT task than to those of MR task.

Previous studies have explored the relationship between LPCs and spatial abilities (Cole et al., 2018); most of these studies have focused on the influence of MR (Black, 2005; Gali & Venukapalli, 2021; Jackson et al., 2015; Wilhelm et al., 2017) by showing a positive correlation between scores of MR tests and those of astronomy concept tests or by demonstrating that students with higher MR abilities showed greater comprehension after learning scientific concepts. However, the present study results demonstrated that when considering the entire problem-solving process, PT has a greater influence than MR on solving LPC problems. MR and PT are distinct mental skills (Hegarty & Waller, 2004); thus, when teaching LPCs, it is necessary to consider the development of students' PT abilities. Zhang et al. (2022) conducted a study involving children aged 6–8 years and suggested that their MR abilities improve with their working memory capacity, consequently improving PT. This suggests that even in children with developed MR ability, the PT ability may not be fully developed. In other words, achieving a better understanding of the concept of LPCs may only be possible when both MR and PT abilities have fully developed.

Spatial ability, such as PT ability, can be enhanced through training (Alias et al., 2002; Newcombe, 2016). Therefore, further research is warranted to identify the stages of PT development in children for appropriate educational support. In this process, defining spatial representation from the perspective of brain activity can be considered an alternative approach, and research on neuroscientific definitions related to mental imagery has already been conducted (Szucs & Goswami, 2007). According to a previous study, cognitive neuroscience can contribute to the understanding of core cognitive areas such as reading and mathematics and making educational decisions that consider the timing (Ansari et al., 2011). Based on the results of the current study and future related research, it will be possible to determine the educational process for introducing the concept of LPCs and provide guidance in real classroom settings while considering the students' developmental stages.

Conclusions and Implications

This study used EEG to analyze the differences in brain activities while solving spatial ability task and LPC task to determine which spatial ability is involved in the LPC task. This was an objective and empirical examination of psychological explanation. Therefore, brain activities were measured while solving the spatial ability task and LPC task, and relative power spectrum analysis and brain activity difference analysis were performed.

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First, compared with MR tasks, significant differences were observed in brain waves in the theta (4–8 Hz) band as well as all four cerebral cortex areas while solving LPC tasks. Additionally, differences were noted in beta (8–13 Hz) band brainwaves in the frontal cortex when solving PT tasks.

Second, significant differences in brain activity were observed between PT and LPC tasks at four different time intervals. When solving PT tasks within 400 ms after task presentation, the medial orbitofrontal cortex and paracentral lobule were activated, whereas the parahippocampal gyrus and superior parietal lobule were activated while solving LPC tasks. After 400 ms, which indicated strategy execution, the occipital lobe and limbic system were mainly activated during PT tasks, whereas the frontal lobe was mainly activated during LPC tasks.

Third, significant differences were observed when comparing the brain activity during MR and LPC tasks. When solving MR tasks within 400 ms after task presentation, which indicated strategy selection, the precuneus, posterior cingulate cortex, fusiform gyrus, and pericalcarine cortex were activated, whereas the caudal anterior cingulate cortex, rostral anterior cingulate cortex, entorhinal cortex, and superior parietal lobule were activated while solving LPC tasks. After 400 ms of task presentation, which indicated strategy execution, the temporal lobe, limbic system, and frontal lobe were activated during both MR and LPC tasks, but the specific brain areas showed distinct time intervals of activation.

Accordingly, the following implications for science education were summarized. First, for students who find it difficult to learn the concept of LPCs, evidence-based neuroscience learning strategies can be provided, as understanding the concept of LPCs requires spatial abilities such as PT, which can be improved through training. Second, although both PT and MR abilities are required for solving LPC tasks, PT was more relevant, as demonstrated through neuroscientific methods. This suggests that the cognitive processes used in solving scientific tasks can be measured in detail using neuroscientific approaches.

Limitations

The current study has certain limitations. First, as specific tasks were used to confirm the relationship between LPC tasks and spatial abilities, there may be limitations in generalizing the results to all spatial abilities or all scientific fields. Second, when developing the LPC, PT, and MR tasks, they were amended based on the opinions of science education experts and preliminary measurement results. However, in this process, biases may arise due to the number, age, and regional characteristics of participants assigned to each task, which may limit the validity and reliability of task selection. These limitations should be clarified through follow-up research using more diverse tasks.

Conflict of Interest

The author(s) declared no conflicts of interest.

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Naeun Lee MEd, Doctoral Student, Korea National University of Education, 250 Taeseongtabyeon-ro, Gangnae-myeon, Heungdeok-gu, Cheongju-si, Chungbuk 28173, South Korea.
E-mail: kkio1109@naver.com
ORCID: https://orcid.org/0000-0002-5314-8055

Ilho Yang PhD, Professor, Korea National University of Education, 250 Taeseongtabyeon-ro, Gangnae-myeon, Heungdeok-gu, Cheongju-si, Chungbuk 28173, South Korea.
E-mail: yih118@knue.ac.kr
ORCID: https://orcid.org/0000-0002-4589-4197

Seongun Kim *(Corresponding author)* PhD, Researcher, Korea National University of Education, 250 Taeseongtabyeon-ro, Gangnae-myeon, Heungdeok-gu, Cheongju-si, Chungbuk 28173, South Korea.
E-mail: auul@naver.com
ORCID: https://orcid.org/0000-0001-7455-6077