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RESEARCH ARTICLE

Comparative Analysis of Brain Activity during Performing Number Sense and Mental Rotational Tasks: An EEG Study Using sLORETA

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수 감각과 공간 회전 과제 수행에 따른 두뇌 활성 비교: sLORETA를 이용한 뇌파연구

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ABSTRACT

This study attempted to find out what differences of the signal sources of brain waves that occurred during performing number sense tasks and mental rotation tasks using sLORETA technology. Twenty students (10 men and 10 women) attending a four-year university in Gyeongsangnam-do were asked to perform six tasks (3 number sense tasks and 3 mental rotation tasks). The EEG brain waves were measured during performing each task and were analyzed by applying to the sLORETA with t-test: paired group test, A-A2=B-B2. The result showed that there were statistically significant differences in theta, alpha, and beta bands between NS1 and NS2, which brain areas included the superior frontal gyrus, the middle frontal gyrus, the inferior frontal gyrus, the superior temporal, the anterior cingulate, the extra-nuclear, and the insula. The anterior cingulate and the superior frontal gyrus were the areas that showed a statistically significant difference between SP2 and SP3 in the gamma band. This study examined the difference in brain activity while performing two different types of tasks by applying sLORETA. It will be expected to deepen the cognitive neuroscience understanding of the mathematics learning process for students.

Key words: Number sense, mental rotation ability, EEG, sLORETA, brain activity

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Introduction

The curiosity about how people engage in mathematics, what processes occur in the brain when solving mathematical problems, is a common topic for many researchers. To address these questions, cognitive psychology has been researching how cognitive processes such as memory, learning, and problem-solving unfold. Recently, there has been an effort to integrate perspectives from cognitive science and neuroscience to understand how specific areas and circuits in the brain contribute to these cognitive functions. The advancements in brain imaging technology have significantly enhanced our understanding of the human brain. In the past, obtaining brain images of the living human was challenging. However, recent advancements in science and medical technology have made it possible to explore the brain activity of living individuals, especially during specific tasks or activities. The technologies that have enabled such research include electroencephalography (EEG), positron emission computed tomography (PET), functional magnetic resonance imaging (fMRI), single-photon emission computed tomography (SPECT), and magnetoencephalography (MEG). Most of these technologies have the disadvantage that the equipment is large, requires a separate measurement location, is not easy to move, so inspection locations are limited, and the cost is high. EEG has a relatively lower spatial resolution compared to other devices but offers the advantage of high temporal resolution. Furthermore, EEG is relatively less affected by examiner's movements, it is noiseless, easily portable, providing flexibility in choosing examination locations, allowing real-time testing even during learning activities, and is cost-effective (Kim et al., 2017). Because EEG measures electrical signals from the scalp, it has the limitation that it is difficult to determine where in the brain the signals originate. EEG source localization techniques developed as a way to compensate for the shortcoming of EEG mathematically calculate and estimate the location and size of the brain signal source. Among them, low resolution electromagnetic tomography (LORETA) is one of the software that implements it (Kang et al., 2017; Kim et al., 2017).

Number sense refers to the ability to use numbers in various ways with an intuitive feeling of numbers, to help one calculate accurately and efficiently, and to use numbers effectively in everyday life (Pang, 2005; Sowder, 1992). Number sense is so important in school mathematics that elementary schools set developing number sense as one of their main goals (NCTM, 1989). Students with a strong number sense demonstrated greater proficiency in mental calculation (Hope & Sherrill, 1987) and computational estimation (Bobis, 1991). There is also research suggesting that the early development of number sense in children may have implications for later mathematical achievement (Gersten et al., 2005).

Spatial ability is the ability to represent, transform, create, and recall symbolic and nonverbal information. It is comprised of spatial perception, mental rotation, and spatial visualization. Spatial perception is the ability to determine spatial relationships with the direction of the subject's own body for a task that contains confusing information. Mental rotation is the ability to quickly and accurately rotate a two-dimensional or three-dimensional object. Spatial visualization refers to the ability to manipulate spatially presented information in complex and multi-step ways (Linn & Petersen, 1985). Battista (1990) highlighted the correlation between spatial ability and mathematical achievement. A study by Casey et al. (1992) also revealed that mental rotation abilities are a significant predictor of mathematical achievement. From elementary school number sense is taught from elementary school through the domains of numbers and operations, while spatial ability is fostered through the domain of geometry. The school mathematics curriculum aims to promote the growth of these two abilities.

According to the results of various cognitive neuroscience studies, there are differences in brain activity patterns when using number sense and when using spatial ability. The intraparietal sulcus (IPS) plays a key role in recognizing and processing quantity. IPS, along with the supramarginal gyrus and angular gyrus, is involved in understanding, comparing, and estimating numbers, and representing mental number line (Kim, 2013; Nieder, 2019). Spatial abilities differed depending on the task used; for the mental rotation task, the dorsolateral prefrontal cortex (DL-PFC), dorsal and ventral visual cortical areas, and superior The superior parietal lobe is activated (Ng, et al., 2001). Particularly, the superior parietal lobe plays a significant role in processing various spatial representations of objects (Halari, et al., 2006). The posterior parietal cortex (PPC) is the region most extensively activated during performance of all visuospatial tasks, including grasping, pointing, eye movements, and spatial attention (Nieder, 2019). Meanwhile, there are brain regions where number sense and spatial ability are interconnected. Zhang & Lin (2017) found a correlation between spatial ability, particularly mental rotation ability, and arithmetic skills. Hubbard et al. (2005) demonstrated that neural circuits that process information related to number sense and spatial abilities share part of the parietal lobe. The numerical and spatial networks overlap in the IPS, consistent with the fact that number and space interact, such that when we mentally recall quantities, we place larger quantities further to the right of the mental number line (Nieder, 2019).

This study collected and analyzed brain activation while performing number sense and mental rotation tasks using EEG technology. Data collected through an EEG device is amplified electrical activity captured by electrodes attached to the scalp (Kang et al., 2017), so the source of the signal cannot be accurately determined. Therefore, this study aims to identify differences in the EEG current sources of participants while performing number sense and mental rotation tasks using sLORETA method, which calculates the location of the signal source. The research question of this study is as follows:

What are the differences in EEG current source when performing number sense tasks and mental rotation tasks, or between each of these tasks?

The aim of this analysis is to derive educational implications for number sense and mental rotation ability, which are distinct but significant skills in mathematics.

Theoretical Background

Number Sense and Spatial Ability

McIntosh et al. (1992) defined "number sense" as "a person's general understanding of number and operations along with the ability and inclination to use this understanding in flexible ways to make mathematical judgments and to develop useful strategies for handling numbers and operations (p.3)." They proposed a framework for basic number sense, identifying three key areas in which number sense plays a crucial role: number concepts, operations with numbers, and applications of number and operation.

• Number Concepts: This refers to knowledge of and facility with numbers. It encompasses a sense of the orderliness of numbers, multiple representations for numbers, a sense of relative and absolute magnitude of numbers, and a system of benchmarks.

• Operations with Numbers: This involves knowledge of and facility with operations. It includes understanding the effect of operations, understanding mathematical properties, and understanding the relationship between operations.

• Applications of Number and Operation: This pertains to applying knowledge of and facility with numbers and operations to computational settings. It includes understanding the relationship between problem context and the necessary computation, awareness that multiple strategies exist, inclination to utilize an efficient representation and/or method, and inclination to review data and results for sensibility (McIntosh et al., 1992).

Subsequently, this framework was distilled into six key elements as follows: (1) understanding of the meaning and size of numbers, (2) understanding and use of equivalent representations of numbers, (3) understanding the meaning and effect of operations, (4) understanding and use of equivalent expressions, (5) flexible computing and counting strategies for mental computation, written computation, and calculator use, and (6) measurement benchmarks" (Reys et al., 1999, p. 62).

This study focused on the task of using numerical benchmarks and effectively applying knowledge related to number and operation skills. Numerical benchmarks serve as mental referents when contemplating numbers. Benchmarks are commonly employed to make judgments about the magnitude of an answer or to facilitate mental rounding for easier computation of numbers. Proficient use of benchmarks when making decisions related to numbers can also serve as an indicator of good number sense (McIntosh et al., 1992). However, Pang (2005) reported difficulties among students in utilizing benchmark scales. When faced with various problem-solving strategies or computational methods in a given problem situation, recognizing and applying a particular strategy or method as more efficient than others is indicative of good number sense (McIntosh et al., 1992). For instance, in complex arithmetic involving a mix of fractions and decimals, a strategy of grouping fractions with fractions and decimals with decimals for computation might be a more effective approach than unifying fractions to decimals or vice versa. However, students accustomed to mechanical calculations often attempt complex computations using the latter method, leading to computational errors. (Pang, 2005).

Researchers have presented diverse definitions and components regarding spatial ability. This section aims to delve into theories associated with the mental rotation task utilized in this study, among the various definitions they have proposed. Yoon (2011) proposed a hierarchical model of spatial ability, integrating factors from Burton & Fogarty (2003), Tartre (1990), and Ho & Eastman (2005) based on the elements identified in Carroll's (1993) analysis (Fig. 1). In this model, mental rotation is considered a subcomponent of spatial visualization. Carroll (1993), after conducting factor analysis and synthesizing findings from various studies, defined spatial visualization as the 'ability in manipulating visual patterns, as indicated by the level of difficulty and complexity in visual stimulus material that can be handled successfully, without regard to the speed of task solution (p.362)'. Tartre (1990) suggested that mental rotation and mental transformation are involved in such manipulations. While mental rotation involves manipulating an entire object, mental transformation is distinguished as manipulating only the partial elements of the object.

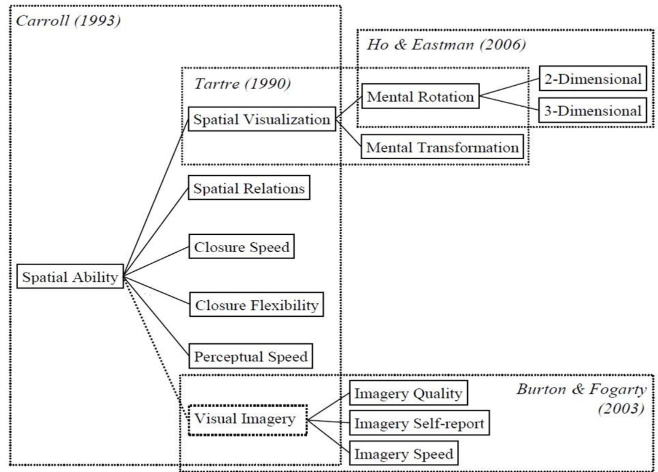

Fig. 1. Hierarchical model of spatial abilities (Yoon, 2011, p. 18)

Types of the Brain Waves

EEG is a method of measuring indirectly through an electric field by attaching conductive electrodes to the scalp to amplify the electrical activity information that occurs when neurons are activated (Kim, et al., 2017). The raw data collected through EEG device is a time series function where the horizontal axis represents time and the vertical axis represents potential, but it is difficult to visually analyze or interpret it. In the analysis of EEG data, fast Fourier transform (FFT) is frequently used for power spectrum analysis, where the horizontal axis represents frequency and the vertical axis indicates the magnitude of the corresponding frequencies present. In other words, spectrum analysis considers EEG signals as linear combinations of specific frequency signals and decomposes these signals into individual frequency components to calculate their magnitudes (Kim et al., 2017; Kim et al., 2017). Spectrum analysis classifies EEG signals into delta, theta, alpha, beta, and gamma waves based on the frequency bands. Delta waves, which dominate during deep sleep (Kim et al., 2017; Kim, 2017), were deemed unnecessary for the analysis in this study, as the research focused on tasks performed during wakefulness, and therefore were excluded. The characteristics of the other major waves, excluding delta waves, are as follows.

Theta waves (4~8Hz) are classified as normal and abnormal brain waves depending on the measurement location and performance factors. Theta waves are primarily manifested in the frontal lobe when performing cognitive tasks, and they are known to be most active during problem-solving processes and when performing spatial memory tasks (Lee, 2021). Theta waves originating in the temporal lobe play an important role in facilitating information exchange between the hippocampus, where memories are temporarily stored, and the cortex, which is the storage area for long-term memories. Theta waves also occur when encoding and retrieving associative learning, spatial memory, and olfactory memory (Buzaki, 2002). There are also research results indicating that theta waves are activated in the parietal lobe when closely observing objects (Kim, 2012). In other studies, it has been reported that as the task difficulty increases, theta wave activity is heightened in the frontal, temporal, and parietal lobes (Fairclough et al., 2005; Jeong & Yun, 2008; Kim & Jeong, 2010).

Alpha waves (8~13Hz) play a role in maintaining relaxation in the brain during learning activities and assist in the appearance of beta waves (Choi, 2004). Alpha waves are known to play a direct role in maintaining a state of attention and enhancing learning effectiveness during information processing (Jung et al., 2006). Alpha waves originating in the frontal lobe are associated with the function of comparing and judging the attributes of objects (Kim, 2012; Sousa, 2009), and they are also related to the performance of complex tasks (Lee, 2021). Alpha waves originating in the temporal lobe are associated with visual working memory (Kim, 2012), while alpha waves from the parietal lobe are related to the integration of visual and spatial information (Lee, 2021). Alpha waves are predominantly observed in the occipital lobe when the eyes are closed, but in an open-eyed state, they appear in the parietal lobe during task performance (Jensen, 2007).

Beta waves (13~30Hz) are widely observed throughout the entire brain when engaging in mental activities that require concentration (Kim & Choi, 2001) and are also used as an indicator of attention along with theta waves (Ko & Shim, 2012; Park & Goo, 2007). Beta waves originating in the frontal lobe are linked to cognitive tasks, particularly when evaluating decisions, engaging in logical reasoning, and problem-solving, especially when listening to or delivering language-based explanations (Lee, 2021). Beta waves tend to be more active in the left frontal lobe than in the right frontal lobe when concentration improves (Kim & Shim, 2010).

Gamma waves (30-50Hz) increase when performing tasks that require high-level cognitive functions (Fitzgibbon et al., 2004). Gamma waves originating in the frontal lobe are associated not only with the processing of simple sensory signals but also with the integration of stimuli into a unified perception of a single object. They are also related to attention, working memory, and memory recall (Hermann et al., 2004). Research has also shown that gamma waves in the frontal lobe occur together with theta waves generated in the hippocampus when long-term and short-term memory operate (O'Keefe & Recce, 1993). Gamma waves originating in the temporal lobe exhibit characteristics related to previously acquired knowledge (Hwang, 2012; Kang, 2015), and are thus closely associated with memory and learning.

EEG Source Localization

When neurons in the brain receive a stimulus, they generate electrical signals to transmit information to other neurons. During this process, current changes occur within the neurons due to ion flow. The current generated by individual neurons is too small to be easily captured by brainwave measuring equipment. EEG, which are the sum of post-synaptic potentials generated by the simultaneous activation of giant pyramidal neurons arranged vertically in the cerebral cortex, is measurable because the direction of the current is the same and the size of the current increases in proportion to the number of activated neurons. EEG is the measurement of the potential difference generated on the surface of the head as the primary currents originating from current sources inside the head (such as cerebrospinal fluid, skull, scalp layer, etc.) with different electrical conductivities. This measurement is performed using at least two electrodes (Hallez et al., 2007; Kim et al., 2017; Lee, 2009).

The process of estimating the location of the signal source based on the potential difference measured at the scalp electrode is referred to as EEG source localization. The process of determining the potential values manifested on the scalp due to electrical activity within the brain is referred to as the forward problem, while estimating the location of the source based on the actual measured scalp potential values is known as the inverse problem. The forward problem has a unique solution, while the inverse problem, being mathematically ill-posed, lacks a unique solution. To pinpoint the source of the signal, this approach involves making specific assumptions regarding factors such as the number of dipoles and their movements. Subsequently, it applies the forward problem to estimate the signal source's location (Kang et al., 2017; Pascual-Marqui, 1999).

There are two approaches to solving the inverse problem in EEG: the non-parametric method and the parametric method. The non-parametric method is referred to as the distributed source model, while the parametric method is known as the single equivalent current dipole model. The single equivalent current dipole model assumes a small number of dipoles with unknown positions and orientations and aims to estimate the positions, orientations, and strengths of these dipoles. This model is better suited for estimating the locations of signal sources that exist in small, localized areas (Kang et al., 2017; Kim et al., 2006; Michel et al., 2004).

Low resolution electromagnetic tomography (LORETA) employs a distributed source model. The distributed source model involves dividing the brain volume into a three-dimensional grid of fixed-size elements, representing all possible source locations, and assumes that dipoles are distributed at each grid point with fixed positions. It aims to estimate the strengths of these dipoles. The distributed source model, unlike the single equivalent current dipole model, does not require a priori assumptions about the number of signal sources, is not affected by the reference electrode, and offers the advantage of obtaining three-dimensional functional imaging. Consequently, it is widely used in solving inverse problems. However, it has the disadvantage of long computation times and low spatial resolution because it cannot accurately determine the precise location and direction of dipoles (Kang et al., 2017; Kim et al., 2006; Michel et al., 2004).

LORETA, which utilizes the distributed source model, applies a smoothing technique to find the sources of recorded potentials on the scalp, assuming that neighboring neurons are activated and synchronized simultaneously (Pascual-Marqui et al., 1994). Smoothing is a technique used to process data by removing noise, fine fluctuations, or discontinuities, thus allowing for the identification of significant patterns within the data. This technique, commonly employed in the fields of signal processing and image processing, is employed in LORETA to determine the most physiologically meaningful and optimal three-dimensional distribution of brain electrical activity (Pascual-Marqui, 1994; Simonoff, 1996; Titterington, 1985). LORETA has been shown to have high accuracy in localizing brainwave sources in simulation experiments, but it has been criticized for its low spatial resolution. In fact, the initial version of LORETA used a three-dimensional grid with 13mm spacing, which was not suitable for adequately reflecting the connectivity of neighboring neurons. Furthermore, the images produced by LORETA can appear somewhat blurry and may produce inappropriate results by localizing regions that are spatially adjacent but functionally disconnected, such as the medial frontal region on both sides (Kang et al., 2017).

Standardized Low Resolution Electromagnetic Tomography (sLORETA)

LORETA exhibits significant accuracy in estimating current sources, but it has limitations that generate localization errors. sLORETA assumes that the distribution of current density includes not only noise from EEG measurements but also biological variations from actual sources of signals. While LORETA uses the Laplacian operator, sLORETA employs statistical nonparametric mapping (SnPM), making it a different concept of localization model compared to LORETA. sLORETA estimates the current density, then normalizes this estimate using the variance and infers localization based on this normalized value. sLORETA has demonstrated through simulation experiments that, in the absence of noise, it achieves zero-error localization for single source origins (Kang et al., 2017; Pascual-Marqui, 2002; Pascual-Marqui, 2009).

sLORETA performs calculations using a realistic head model and estimates the source locations using the MNI152 template for visualization. MNI is standardized by the Brain Imaging Center at the Montreal Neurological Institute and is a scan of the brain volume with a spatial resolution of 5 mm. In sLORETA, the cerebral cortex is divided into 6,239 voxels, each measuring 5 × 5 × 5 mm. sLORETA primarily generates MNI coordinate values, but it also offers transformed values into Talairach coordinates, which provide a more detailed description of the Brodmann Area (BA) (Brett et al., 2001; Pascual-Marqui, 2002). In 1909, Brodmann classified brain regions based on characteristics such as shape, cellular layers, and density of brain cells. He represented each of these regions numerically, and these numerical representations are what we now refer to as Brodmann areas (Slotmick, 2021).

sLORETA provides SnPM as a statistical analysis method to test voxel-to-voxel differences. SnPM is based on the permutation test, which is one of the nonparametric testing methods. The permutation test has the advantage that it does not depend too much on the sampling method and can be used even if the distribution does not satisfy normality(Nichols & Holmes, 2001). The SnPM applied in sLORETA operates as follows: A new group is formed by randomly shuffling the components of the original group, ensuring that the new group includes more than half of the original group's components for comparison across different frequency bands. After that, the process of comparing voxel-to-voxel is repeated a specified number of times (default value is 5,000) for the 6,239 voxels. During each iteration, the largest t-value calculated is stored. Then, a critical value is selected from the upper α × 100% of the t-value distribution to ensure that the -value is below the significance level (Kim & Jin, 2005).

Methodology

Participants

Twenty adults, consisting of 10 men and 10 women (M=21.1, SD=1.45), who were attending a 4-year university in Gyeongsangnam-do, participated as subjects in this study. Through a preliminary investigation, all research participants were identified as right-handed, and none had any cognitive history affecting brainwaves. They also did not exhibit any cognitive symptoms, such as dyslexia or dyscalculia, which would hinder their performance in the tasks used in this study. Before starting the experiment, they were informed about the purpose of the experiment and the non-invasive nature of the brainwave measurement process, ensuring that there would be no aftereffects on their bodies. After signing the informed consent form, they proceeded with the experiment. EEG measurements were conducted after the participants had entered the laboratory and had an adequate period of rest. Additionally, if any abnormal symptoms occurred after participating in the experiment, they were instructed to contact the experiment coordinator. This study was approved by the Korea National Institute for Bioethics Policy IRB (approval No. P01-201804-11-001).

Instruments

This study employed two types of tasks: number sense tasks and mental rotation ability tasks. The study selected three items from those presented by Pang (2005) that corresponded to the number sense elements of utilization of benchmarks and adequate utilization of knowledge. These three items are listed in Table 1, and each item was coded as NS1, NS2, and NS3, respectively.

Table 1. Number sense tasks

Number sense component	Evaluation details	Task
Utilization of benchmarks	Arrangement of decimals and fractions using a benchmark	NS1. Without directly calculating them, find the largest and the smallest numbers from the following: ① $\frac{9}{10}$ ② $\frac{20}{39}$ ③ $\frac{19}{40}$ ④ 0.75 ⑤ $\frac{15}{13}$ ⑥ $\frac{1}{2}$
Adequate utilization of knowledge	Mixed calculation of mixed fractions and decimals	NS2. Calculate the following: $4\frac{3}{4}+13.6+7\frac{2}{8}-7.9+4.3$
	Selecting adequate numbers to make a certain number	NS3. Are their four numbers that can be multiplied, each number being used only once, to produce 4335? If so, choose those number, and if not, explain why. 14 10 8 15 28 4 9 5 12 2

As the mental rotation ability tasks, three questions were selected from the Revised Purdue Spatial Visualization tests: Visualization of Rotations (revised PSVT:R) (Yoon, 2011). This test is an evaluation tool that focuses on mental rotation ability among the components of spatial ability. In particular, it measures spatial visualization ability for mental rotation of three-dimensional objects. It has been used worldwide for over 30 years to investigate the relationship between students' academic achievement and their spatial abilities in the fields of science, technology, engineering, and mathematics (Guay, 1976; Yoon, 2011). The internal consistency reliability of the Korean version of PSVT:R used in this study was Cronbach's $\alpha = 0.862$, and the result of confirmatory factor analysis indicated that PSVT:R had good validity. In this experiment, three items with varying difficulty levels from the total of 30 items in the PSVT:R were selected. The selected items for this study were Item 1, Item 12, and Item 22, with item difficulty levels of 0.827, 0.609, and 0.428, respectively. For convenience in this study, these items were coded and named as SP1, SP2, and SP3, corresponding to Item 1, Item 12, and Item 22 (Park, 2012; Yoon, 2011).

Procedure

This study was conducted through the following processes: 1) selection of task items, 2) preliminary EEG measurement experiment, 3) main EEG measurement experiment, 4) artifact removal of EEG data, and 5) sLORETA analysis. Prior to the main experiment, a pilot experiment was conducted once, and the research procedure was modified based on this. In this study, the researcher first measured baseline EEG in a resting state, then recorded EEG while solving number sense tasks. Subsequently, EEG were recorded while participants were solving mental rotation ability tasks.

Since the tasks required participants to keep their eyes open while solving them, resting-state EEG data with eyes open were collected and used as a reference for comparison with the EEG recorded during task performance. This approach aims to prevent the potential increase in alpha waves that can occur with eyes closed. The task presentation paradigm is illustrated in Fig.2.

• Baseline EEG measurement in a resting state with eyes open (participants gaze at a "+" sign on the computer screen for 60 seconds).

• EEG recording during the performance of three number sense tasks (each task lasting 60 seconds).

• Approximately 5 minutes of rest for participants before the mental rotation ability tasks to allow for the dissipation of any lingering brain wave effects from the number sense tasks.

• EEG recording during the performance of mental rotation ability tasks (following a similar process to the number sense tasks).

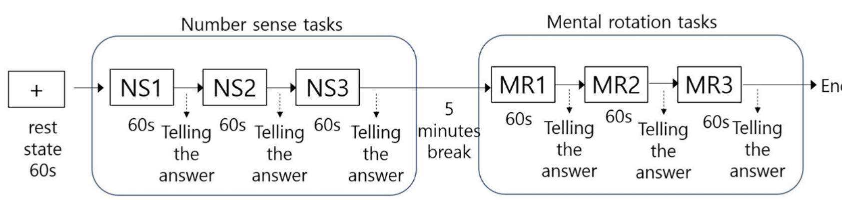

Fig. 2. Task presentation paradigm

Procedure

The EEG measurement device used in this study was Bios-S24, and using Bios single (Biobrain Co., Daejeon, Korea) software, brain waves were collected by classifying 10 important brain regions into each channel. The electrodes that were attached to the selected ten regions were placed using a conductive gel for safe electrode application, following the 10-20 international standard electrode placement method, on the locations of the prefrontal lobes (Fp1, Fp2), frontal lobes (F3, F4), temporal lobes (T3, T4), parietal lobes (P3, P4), and occipital lobes (O1, O2). Additionally, the reference electrode was attached behind the right ear and the ground electrode was attached to the back of the neck (Fig. 3).

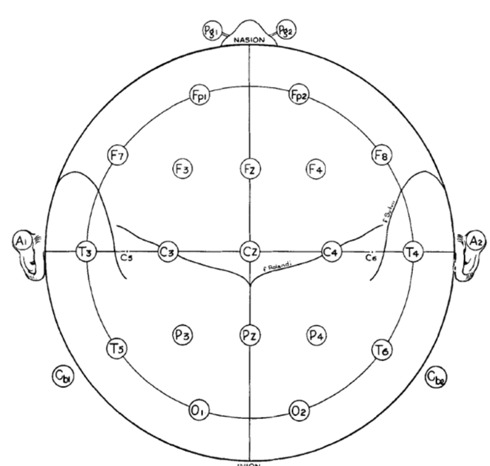

Fig. 3. 10-20 Electrode Placement Method (Jasper, 1958, p. 374)

The sampling rate was 250Hz, and 60Hz was used as a notch filter to remove commercial AC noise caused by AC induction. The collected EEG signal data was preprocessed to remove artifacts using the analysis program Telescan (Laxtha Inc., Daejeon, Korea). The data with artifacts removed were processed using sLORETA software to analyze the sources of statistically significant brain activity between tasks.

The software used for the localization of EEG signal sources in this study was LORETA-KEY, free academic software provided by the KEY Institute for Brain-Mind Research; https://www.uzh.ch/keyinst/loreta. The frequency bands used in the sLORETA analysis for this study are theta (4-7.9Hz), alpha (8-12.9Hz), beta (13-29.9Hz), and gamma (30-50Hz). The sLORETA analysis procedure included creating text files in .slor format for each subject's EEG raw data and then performing a paired group t-test (A-A2=B-B2), where A2 and B2 represented the eyes-opened resting state. A paired-samples t-test rather than an independent sample t-test was conducted, because the purpose was to determine differences in brain activation when performing two paired tasks for the same subject. Differences between voxel to voxel in all frequency bands were tested using the SnPM method. Under the null hypothesis that there is no difference in brain activation between two paired tasks, this method involved randomly creating new groups by mixing more than half of the original comparison group members, calculating t-values for the mean differences between the two groups. This process was repeated 5000 times, and voxels with t-values exceeding the threshold for were considered as neurophysiological current source generators with statistically significant differences in brain activity between the two groups. In this study, t-values were calculated for log-transformed data to ensure better normality by reducing data dispersion (Curran-Everett, 2018). This process was repeated 5000 times, and voxels with t-values exceeding the threshold for $p<0.05$were considered as neurophysiological current source generators with statistically significant differences in brain activity between the two groups (Kim & Jin, 2005).

Results and Discussions

Out of a total of 6 tasks (3 number sense tasks NS1, 2, 3, and 3 mental rotation ability tasks SP1, 2, 3), when paired together for sLORETA analysis, statistically significant differences in brain activation were observed only in NS1-NS2 and SP2-SP3.

NS1-NS2

The critical values for the significance probabilities obtained from the statistical analysis of NS1-NS2 using the sLORETA are shown in Table 2.

Table 2 . Critical values for each p-value (NS1-NS2)

hypothesis test \ p-value	t(0.01)	t(0.05)	t(0.10)	ExtremeP
one-tailed (A>B)	3.860	3.327	3.051	0.678
one-tailed (A<B)	-3.834	-3.342	-3.075	0.001
two-tailed (A<>B)	4.052	3.566	3.331	0.002

The present study aims to investigate whether there are differences in brain activation during the performance of two types of tasks. Therefore, the alternative hypothesis was formulated as the two-tailed hypothesis, stating that there is a difference in brain activation when performing NS1 and NS2 tasks, with a significance level set at 0.05. The critical value was t=3.566, and the extreme *p*-value was *p*=0.002. Under the null hypothesis that 'there is no difference in brain activity between NS1 and NS2,' if a value exceeding the threshold is observed at the $p<0.05$ in any of the 5,000 randomization processes, the null hypothesis is rejected. In other words, voxels in the Talairach space with t-values exceeding the critical values at $p<0.05$ are considered as sources of current signal with statistically significant differences. The analysis of NS1-NS2 results for each frequency band, comparing the absolute values of maxLOR to the threshold of 3.566, yielded the following results: theta maxLOR=4.444, alpha maxLOR=4.135, beta maxLOR=4.109, and gamma maxLOR=3.080. This confirms that the theta, alpha, and beta frequency bands exhibit statistically significant differences in brain activation.

Theta (4~7.9Hz)

The sLORETA statistical test results for NS1-NS2 showed that theta maxLOR=4.444, which is greater than the critical value 3.566, indicating a significant difference in the theta frequency band. With a significance level of 0.05 and a critical value of 3.566, a total of 284 voxels were found to be statistically significant, mainly located in the right brain. The detailed information about the brain regions that exhibited significant differences between the performance of NS1 and NS2 in the theta frequency band is shown in Table 3. Table 3 presents representative information about the regions that exhibit the most significant differences among those showing significant differences.

Table 3. The results of difference in brain activity between NS1 and NS2 (theta) (*the number in brackets means the total number of voxels in which the structure appears)(R: right, L: left)

MNI Coordinates			Voxel Value	Brodmann area	Lobe	Structure*
X	Y	Z				
40	10	-10	-4.444	13(R)	Sub-lobar	Extra-Nuclear (6)
35	15	-5	-4.431	13(R)	Sub-lobar	Insula (24)
40	15	-10	-4.360	47(R)	Frontal Lobe	Inferior Frontal Gyrus (105)
45	10	-10	-4.359	38(R)	Temporal Lobe	Superior Temporal Gyrus (45)
55	10	-20	-4.158	21(R)	Temporal Lobe	Middle Temporal Gyrus (14)
15	40	15	-4.031	32(R)	Limbic Lobe	Anterior Cingulate (3)
25	50	40	-3.993	9(R)	Frontal Lobe	Superior Frontal Gyrus (28)
30	45	40	-3.970	9(R)	Frontal Lobe	Middle Frontal Gyrus (51)
50	15	10	-3.768	44(R)	Frontal Lobe	Precentral Gyrus (6)
30	5	-20	-3.591	34(R)	Limbic Lobe	Parahippocampal Gyrus (1)
40	-5	-10	-3.567	21(R)	Temporal Lobe	Sub-Gyral (1)

Fig.4 depicts the location of the theta wave generation signal source where significant differences between the two tasks appear. The area with the most significant difference in activation between two tasks was the extra-nuclear (BA13) of the sub-lobar area of the right brain.

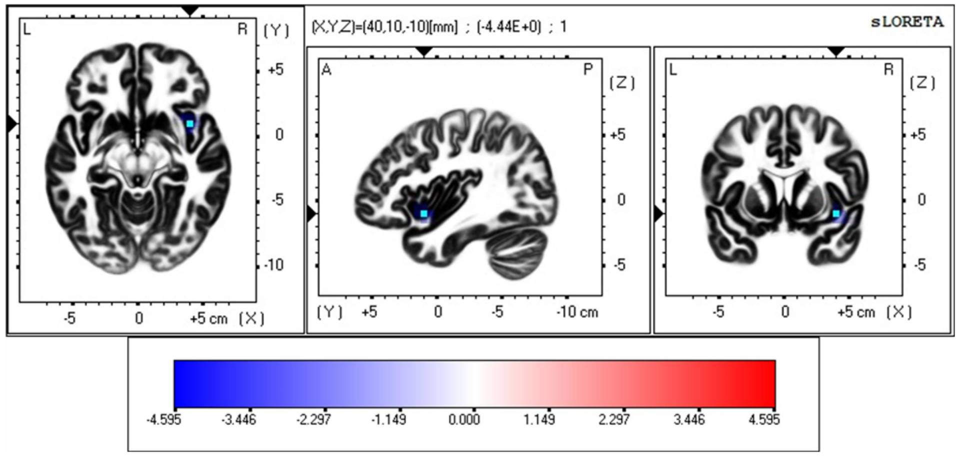

Fig. 4. The areas showing difference in brain activity between NS1 and NS2 (theta)

Theta waves originating in the frontal lobe are associated with performing cognitive tasks, while theta waves originating in the temporal lobe are related to memory processing (Buzaki, 2002; Lee, 2021). It is known that the higher the difficulty of the task, the higher the theta activity in the frontal, temporal, and parietal lobes (Fairclough et al., 2005; Jeong & Yun, 2008; Kim & Jeong, 2010). In this study, higher brain activation was observed in the inferior frontal gyrus, superior temporal gyrus, middle temporal gyrus, superior frontal gyrus, and middle frontal gyrus, which belong to the frontal and temporal lobe areas, during NS1 performance. This can be interpreted as indicating that NS2 was more difficult compared to NS1, consistent with previous research findings.

The insula, located in the sub-lobar region, is an area involved in perceiving emotions. Although the functions of the insula are not fully understood, one consistent aspect often reported in relation to cognitive functions is that the insula is involved in the detection of new stimuli across sensory modalities (Uddin et al., 2017). Based on these research findings, it can be interpreted that NS2 was perceived as more novel stimuli by the participants compared to NS1.

Alpha (8~12.9Hz)

In the alpha frequency band, there were significant differences between NS1 and NS2 performance, with a total of 318 voxels in the right brain. The detailed information about the brain regions showing significant differences between two tasks in the alpha frequency band is provided in Table 4.

Fig.5 depicts the location of the alpha wave generation signal source where significant differences between the two tasks appear. The area with the most significant difference in activation between two tasks was the right inferior frontal gyrus (BA47) of the frontal lobe.

Alpha waves typically appear prominently in the posterior regions of the brain, but alpha waves observed in the anterior areas are associated with inner states such as meditation, tranquility, and serenity (Kim et al., 2017). In the context of emotions, there are findings suggesting that left brain's middle frontal area's alpha wave dominance is linked to positive emotions, while right brain's alpha wave dominance is associated with negative emotions (Chung, 2007; Chung & Yoon, 2008). In this study, the increased activation of alpha waves in the right brain, especially in the inferior and middle frontal regions, during NS2 performance compared to NS1 suggests the emergence of more negative emotions during NS2 tasks. With a correct answer rate of 95% for NS1 and only 15% for NS2, it can be inferred that participants found NS2 to be more challenging, potentially leading to negative emotions.

Table 4. The results of difference in brain activity between NS1 and NS2 (alpha)

MNI Coordinates			Voxel Value	Brodmann area	Lobe	Structure
X	Y	Z				
45	15	-5	-4.135	47(R)	Frontal Lobe	Inferior Frontal Gyrus (116)
50	15	-5	-4.126	22(R)	Temporal Lobe	Superior Temporal Gyrus (43)
40	15	-5	-4.125	47(R)	Sub-lobar	Insula (27)
35	20	0	-4.095	47(R)	Sub-lobar	Extra-Nuclear (6)
35	40	15	-4.024	10(R)	Frontal Lobe	Middle Frontal Gyrus (70)
35	50	25	-4.015	10(R)	Frontal Lobe	Superior Frontal Gyrus (32)
20	40	15	-3.923	32(R)	Limbic Lobe	Anterior Cingulate (4)
55	15	10	-3.922	44(R)	Frontal Lobe	Precentral Gyrus (12)
60	5	-10	-3.921	21(R)	Temporal Lobe	Middle Temporal Gyrus (8)

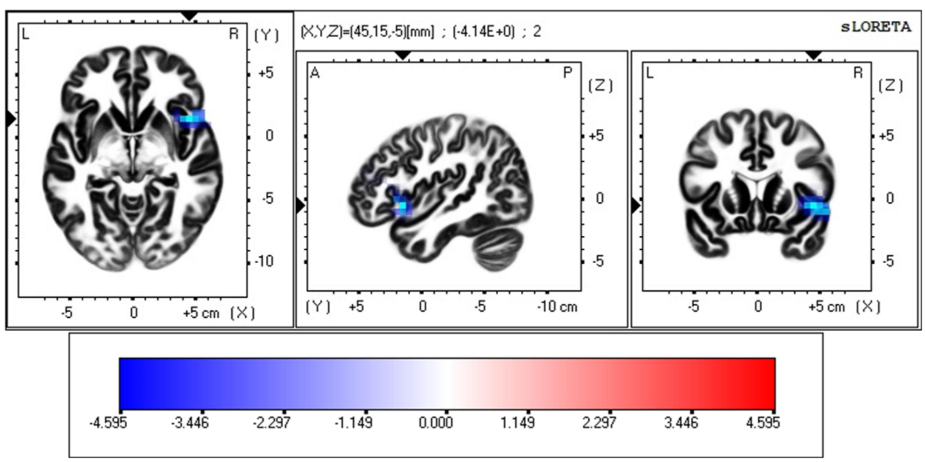

Fig. 5. The areas showing difference in brain activity between NS1 and NS2 (alpha)

The right inferior frontal gyrus, which showed the most significant difference in alpha activation in this study, is known to be associated with various cognitive functions, including social cognition, language, attention, motor inhibition, and mental imagery. Additionally, it is known to be involved in risk avoidance during decision-making related to risk (Christopoulos et al., 2009). Research findings also indicate that the right inferior frontal gyrus plays an important role in the process of response inhibition, which involves intentionally delaying habitual or dominant responses (Hamsphire et al., 2010). Study attempting to functionally differentiate the right inferior frontal gyrus has reported that the posterior inferior frontal gyrus is associated with behavioral inhibition and execution, while the anterior inferior frontal gyrus is associated with reasoning and social cognitive processes (Hartwigsen et al., 2019).

Alpha waves are related to inhibition; an increase in alpha reflects inhibition and a decrease in alpha reflects release from inhibition. Specifically, it is known that human brains become more aroused when retrieving semantically well-integrated information compared to retrieving less integrated information. Inhibitory alpha wave activity is related to attention during information processing. In other words, for tasks that require focused attention, alpha waves enhance and sharpen that attention while blocking out distractions from tasks outside of the focused activity (Klimesch, 2012). The results of this study, showing an increase in alpha wave activity in the inferior frontal gyrus during NS2 performance compared to NS1, suggest that participants' brain activity was more active in inhibitory functions during NS2 tasks. This can be interpreted as indicating a greater focus on selective attention in the NS2 task.

Beta (13~29.9Hz)

In the beta frequency band, there were significant differences between NS1 and NS2 performance, with a total of 303 voxels in the right brain. The detailed information about the brain regions showing significant differences between two tasks in the beta frequency band is provided in Table 5.

Table 5. The results of difference in brain activity between NS1 and NS2 (beta)

MNI Coordinates			Voxel Value	Brodmann area	Lobe	Structure
X	Y	Z				
50	45	10	-4.109	46(R)	Frontal Lobe	Middle Frontal Gyrus (111)
45	40	10	-4.072	46(R)	Frontal Lobe	Inferior Frontal Gyrus (111)
40	50	25	-4.072	10(R)	Frontal Lobe	Superior Frontal Gyrus (41)
20	45	10	-3.902	32(R)	Limbic Lobe	Anterior Cingulate (14)
45	20	-15	-3.877	38(R)	Temporal Lobe	Superior Temporal Gyrus (15)
30	25	0	-3.855	13(R)	Sub-lobar	Insula (7)
30	20	-10	-3.756	47(R)	Frontal Lobe	Extra-Nuclear (3)
20	30	-25	-3.596	47(R)	Frontal Lobe	Orbital Gyrus (1)

Fig.6 depicts the location of the beta wave generation signal source where significant differences between the two tasks appear. The area with the most significant difference in activation between two tasks was the right middle frontal gyrus (BA46) of the frontal lobe.

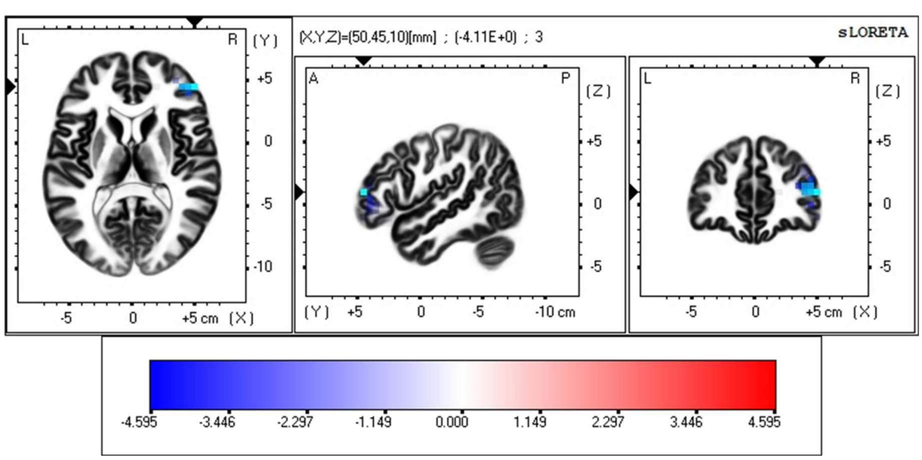

Fig. 6. The areas showing difference in brain activity between NS1 and NS2 (beta)

Beta waves observed in the frontal lobe are predominantly active during cognitive tasks, particularly when evaluating or making decisions about stimuli. The level of beta wave activity is related to the level of activity or stimulation of the cortical area, so excessively generated beta waves indicate cortical overactivity or overstimulation (Kim et al., 2017). Thus, increased activation of beta waves in the frontal lobe, especially the right middle frontal gyrus, during the NS2 task compared to NS1 suggests a higher level of cortical activity during the more challenging NS2 task.

Beta waves are a widely distributed brainwave pattern that occurs throughout the brain during mentally demanding activities (Kim & Choi, 2001). They are also used as an indicator of attention, often in conjunction with theta waves (Ko & Shim, 2012; Park & Goo, 2007). Beta waves observed in the frontal lobe are associated with performing cognitive tasks that involve evaluation, decision-making, logical reasoning, problem-solving, and listening to or speaking language-based explanations (Lee, 2021). Furthermore, when concentration improves, there is a tendency for greater activation in the left frontal lobe than in the right frontal lobe (Kim & Shim, 2010).

SP2-SP3

The critical values for the significance probabilities obtained from the statistical analysis of tasks SP2-SP3 using sLORETA are shown in Table 6.

Table 6 . Critical values for each *p*-value (Sp2-Sp3)

p-value / hypothesis test	t(0.01)	t(0.05)	t(0.10)	ExtremeP
one-tailed (A>B)	3.253	2.834	2.609	0.909
one-tailed (A<B)	-3.288	-2.864	-2.614	0.016
two-tailed (A<>B)	3.420	3.059	2.850	0.034

The analysis of the difference in brain activation between SP2 and SP3 was conducted with a significance level of 0.05. The alternative hypothesis was set as the presence of a difference in brain activation when performing SP2 and SP3 tasks. The critical value was t=3.059, and the extreme *p*-value was calculated as *p*=0.034. To evaluate differences in brain activation by frequency band, the absolute values of maxLOR from the SP2-SP3 analysis results were compared to the critical value of 3.059 for statistical significance. With theta maxLOR=2.3432, alpha maxLOR=2.2100, beta maxLOR=2.6377, and gamma maxLOR=3.1537, it can be observed that only in the gamma frequency band, the maxLOR value exceeded the threshold, indicating a statistically significant difference.

A total of two voxels exhibited significant differences in brain activity in the gamma band during the SP2-SP3 tasks, and the details are provided in Table 7.

Table 7. The results of difference in brain activity between SP2 and SP3 (Gamma)

MNI Coordinates			Voxel Value	Brodmann area	Lobe	Structure
X	Y	Z				
5	35	20	-3.154	32(R)	Limbic Lobe	Anterior Cingulate Gyrus
5	55	30	-3.093	9(R)	Frontal Lobe	Superior Frontal Gyrus

Fig. 7 depicts the locations of the sources of significant differences in gamma wave generation signals between the two tasks. The area where the most significant difference in activation was observed during the performance of both tasks is the right anterior cingulate (BA32).

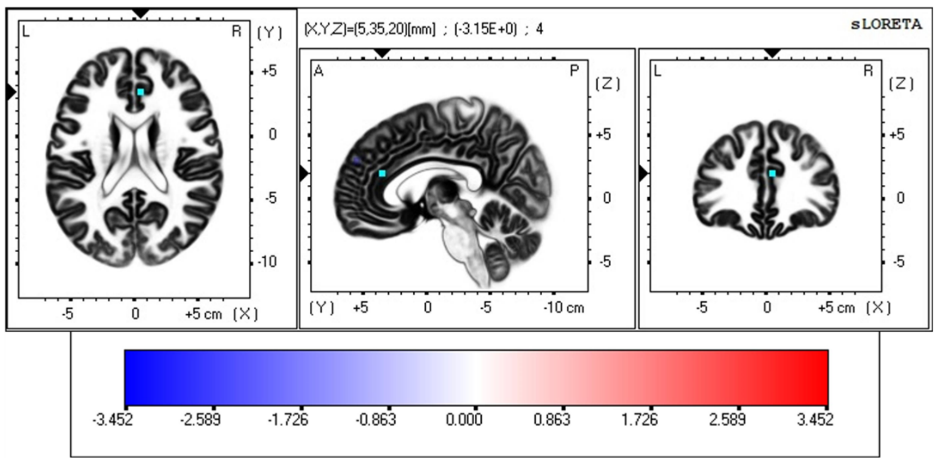

Fig. 7. The areas showing difference in brain activity between SP2 and SP3 (gamma)

Gamma waves are relatively high-frequency oscillations and their generation is associated with tasks requiring higher-order cognitive functions such as reasoning and judgment. They also increase during emotionally aroused states, particularly more prominently in the frontal lobes (Fitzgibbon et al., 2004; Young & Taylor, 1998; Freeman et al., 2003). The findings suggesting increased gamma wave activity in the superior frontal gyrus during the performance of task SP3 compared to task SP2 indicate that SP3 may involve more complex cognitive processes.

The anterior cingulate gyrus is responsible for concentration of attention according to goal setting, working memory such as monitoring, and is involved in higher-order thinking and problem solving (Kim, 2013). The anterior cingulate gyrus is associated with a wide range of cognitive activities, including attentional processes that elicit emotional responses (Posner & Petersen, 1990; Bush et al., 2000), decision-making related to rewards (Botvinick et al., 2004), error detection (Jessup et al., 2010), and behavioral response selection and inhibition (Paus, 2001). The significant activation difference in the anterior cingulate gyrus area during SP3 compared to SP2 can be interpreted as SP3 requiring greater attention and a higher working memory load than SP2.

Discussions

The EEG frequency bands that exhibited differences between NS1 and NS2 performances were theta, alpha, and beta. The regions where differences were observed in the theta band, sorted by frequency, are as follows: inferior frontal gyrus, middle frontal gyrus, superior temporal gyrus, superior frontal gyrus, insula, middle temporal gyrus, extra-nuclear, precentral gyrus, anterior cingulate, parahippocampal gyrus, sub-gyral. In the alpha band, the areas showing differences, ranked by frequency, are: inferior frontal gyrus, middle frontal gyrus, superior temporal gyrus, superior frontal gyrus, insula, precentral gyrus, middle temporal gyrus, extra-nuclear, anterior cingulate. Finally, in the beta band, the regions with differences, listed by frequency, are: middle frontal gyrus, inferior frontal gyrus, superior frontal gyrus, superior temporal gyrus, anterior cingulate, insula, extra-nuclear, orbital gyrus.

Some Research findings indicate that the activation of the right middle frontal gyrus and inferior frontal gyrus increases with the complexity of the task. This is attributed to the heightened cognitive demands such as working memory, sustained attention, and planning as tasks become more complex, and these cognitive processes are associated with the prefrontal cortex (Fehr et al., 2007; Soltanlou et al., 2017). NS1 involves numerical magnitude comparison, while NS2 deals with addition and subtraction operations. Hawes et al. (2019) reported differences in brain activation between symbolic number processing and arithmetic. Since their study primarily synthesized results for whole numbers, variations may exist compared to the results of our study involving fraction-based tasks. However, considering the potential for similar phenomena in a broader number system, further research is needed to explore the differences in brain activation between the comparison and manipulation of rational numbers, not limited to whole numbers.

The EEG frequency band that exhibited differences during the performance of SP2 and SP3 was the gamma band, and the brain regions involved were the anterior cingulate gyrus and superior frontal gyrus. SP2 requires a 180-degree rotation in the x-axis direction, while SP3 involves a 90-degree rotation in the positive y-axis direction followed by a 90-degree rotation in the negative z-axis direction. According to Nikolaev & Anokhin (1998), the angle difference of presented shapes for mental rotation not only affects EEG rhythms but also influences the level of cortical activation. Based on such research findings, the difference in rotation angles between SP2 and SP3 can be interpreted as influencing brain activity. The observed difference between SP2 and SP3 occurred in the gamma band, and previous studies have suggested a relationship between decreased gamma band activity and cognitive processing (Hirata et al., 2004; Lachaux et al., 2008; Thomas et al., 2013). Therefore, it can be inferred that the difference in cognitive processing during the performance of these tasks influenced the activation in the gamma band. Subsequent research is needed to explore the specific characteristics of the tasks contributing to this difference in cognitive processing.

In this study, there were no significant differences observed in the performance of number sense tasks and mental rotation tasks. This could be interpreted as indicating no differences because the brain regions involved in handling numbers and those involved in spatial processing are interconnected. Hawes et al. (2019) conducted an fMRI meta-analysis on symbolic number processing, arithmetic, and mental rotation. They introduced two theories to explain the neural overlap phenomenon in number, arithmetic, and mental rotation tasks. One is the 'general magnitude theory,' which argues that all three types of tasks involve comparisons and judgments related to magnitude (Walsh, 2003). The other is the 'neuronal recycling hypothesis,' suggesting that specific brain regions or circuits are not newly formed to handle particular functions, but rather existing brain circuits take charge of handling new functions. In other words, when performing number and arithmetic tasks, spatial and motor-related brain circuits are recycled (Dehaene & Cohen, 2007).

Conclusions and Implications

This study aimed to elucidate the changes in the sources of brain wave currents during the performance of a set of number sense tasks and mental rotation ability tasks using EEG through sLORETA. The research results revealed through sLORETA analysis are summarized as follows. The tasks pairs with statistically significant differences were NS1 and NS2, as well as SP2 and SP3. First, differences in activation were observed between NS1 and NS2 in the theta, alpha, and beta frequency bands. In the theta frequency band, the brain regions that showed differences were the right extra-nuclear, insula, inferior frontal gyrus, superior temporal gyrus, middle temporal gyrus, anterior cingulate gyrus, superior frontal gyrus, and middle frontal gyrus. According to previous research, theta waves occurring in the frontal and temporal lobes are related to cognitive task performance and memory processing (Buzaki, 2002; Lee, 2021), and theta wave activity is high in these areas depending on the difficulty of the task (Fairclough et al., 2005; Jeong & Yun, 2008; Kim & Jeong, 2010). Based on these results, it can be interpreted that NS2 had a higher level of difficulty a more challenging cognitive task performance than NS1. The brain regions where differences in activation in the alpha band were observed between NS1 and NS2 were the inferior frontal gyrus, superior temporal gyrus, insula, extra-nuclear, middle frontal gyrus, superior frontal gyrus, and anterior cingulate in the right brain. Based on previous research indicating that alpha waves in the front part of the brain are associated with internal states (Kim et al., 2017) and that right hemisphere alpha dominance is linked to negative emotions (Chung, 2007; Chung & Yoon, 2008), the findings of this study suggest that NS2, compared to NS1, may have been influenced by negative emotions such as the difficulty of the task. The brain regions that showed activation differences in the beta band between NS1 and NS2 were the middle frontal gyrus, inferior frontal gyrus, superior frontal gyrus, anterior cingulate, superior temporal gyrus, insula, and extra-nuclear of the right brain. Based on previous research indicating that beta waves originating in the frontal lobe are activated during cognitive tasks related to decision-making, logical reasoning, and problem-solving (Lee, 2021), it can be interpreted that NS2, compared to NS1, was a task that required higher-order cognitive performance.

Next, SP2 and PS3 showed differences in activation only in the gamma band, and the regions were the anterior cingulate and superior frontal gyrus. Gamma waves are known to be activated during higher-order cognitive functions, especially gamma waves originating in the frontal lobe are associated with intense emotions (Fitzgibbon et al., 2004; Freeman et al., 2003; Young & Taylor, 1998). The difficulty levels for the three items were 0.827, 0.609, and 0.428, respectively, indicating that SP3 was the most difficult item. From this perspective, in the current study, participants exhibited higher levels of anxiety while performing SP3, which may be related to the task difficulty. Based on previous research suggesting that the anterior cingulate is involved in working memory, attention, and higher-order thinking (Kim, 2013), it can be interpreted that SP3, compared to SP2, required higher working memory load, greater attention, and more cognitive activity.

While designing this study, it was anticipated that there might be differences in the EEG signals when performing a number sense task and a mental rotation task. However, in reality, there were no statistically significant differences in the signals between the number sense task and mental rotation task. Instead, differences were observed between tasks within each area. Here are some plausible reasons why this happened: Several studies have shown that number sense and spatial abilities are interconnected. Some neural circuits in the parietal lobe overlap when processing number sense and spatial abilities (Hubbard et al., 2005). Dehaene et al. (1993) conducted a test where participants were presented with numbers from 1 to 10 and were asked to classify whether each number was even or odd by pressing one of two keys. When responding using the left side, the response was to small numbers such as 1 or 2. was faster, and when responding to the right, it was discovered that the response to large numbers was faster. They named the result indicating that spatial orientation influences response times for numbers the Spatial-Numerical Association of Response Codes effect (SNARC effect). So when we think about numbers, we assume the formation of a mental number line, which we use to compare the magnitudes of two numbers. In cultures that read from left to right, it is assumed that smaller numbers are placed to the left on the mental number line, and larger numbers to the right (Nieder, 2019). As number sense and spatial abilities share neural circuits, there might not have been differences in brain activation when performing tasks of these two types.

After considering the limitations uncovered by this study, the proposed follow-up research is as follows. Firstly, both tasks in which differences were observed in number sense are related to the area of fractions and decimals. The first task involves comparing the sizes of fractions and decimals, while the second task deals with addition and subtraction of fractions and decimals. The difference in the mathematical content being addressed could have influenced the brain activation patterns. However, this is speculative, and to substantiate this, further research is needed to identify which brain areas are activated when performing fraction and decimal size comparisons and calculations. Furthermore, while the present study did not reveal differences in brain activation between tasks using fractions/decimals and tasks using whole numbers, further research is necessary to investigate which brain regions are activated when processing whole numbers compared to fractions/decimals. It is also crucial to identify the areas that are commonly activated and those that show differences. Secondly, the mental rotation task employed three items with varying levels of difficulty, but interestingly, no statistically significant differences in cognitive activity were observed, particularly between the tasks with a larger difficulty gap, such as SP1 and SP3. One possible explanation for these results could be differences in problem-solving strategies. According to the problem-solving strategy presented by Yoon (2011), SP1 requires a 90° rotation in the positive x-axis direction, while SP2 requires a 180° rotation in the x-axis direction. SP3 must rotate 90° in the positive y-axis direction and then 90° in the negative z-axis direction, or rotate 90° in the positive z-axis direction and then rotate 90° in the negative y-axis direction. Further research is needed to understand how these differences in problem-solving strategies impact cognitive activity in the brain.

The significance of this study lies in its attempt to apply EEG and the sLORETA technology commonly used in neuroscience to the field of mathematics education. It aimed to understand the relationship between brain activity while performing mathematical tasks, such as number sense and mental rotation abilities. Learning mathematics involves more than just calculations; it requires higher-order cognitive activities such as problem-solving skills and mathematical reasoning. Each student comes with varying levels of prior knowledge and understanding, and the differences in learning approaches can result in variations in mathematical task performance outcomes. The sLORETA analysis technique allows us to analyze how students' brains are activated during solving mathematical tasks or problems. Based on the information obtained from these analyses, we can determine which types of mathematical activities are more suitable for students' brain activity and identify approaches that can maximize learning outcomes. This enables the planning of individualized mathematics learning activities for students. In particular, by identifying common brain activation patterns in students when learning specific concepts, it is expected that cognitive neuroscientific approaches can provide assistance to students experiencing mathematical difficulties related to those concepts. Therefore, research in the field of mathematics education that utilizes EEG and sLORETA is expected to provide a deeper understanding of students' cognitive learning, mathematical reasoning, and mathematics learning theory.

References

Battista, M. T. (1990). Spatial visualization and gender differences in high school geometry. Journal for Research in Mathematics Education, 21, 47-60.

Bobis, J. (1991). The effect of instruction on the development of computation estimation strategies. Mathematics Education Research Journal, 3, 7-29.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. Trends in Cognitive Sciences, 8, 539-546.

Brett, M., Christoff, K., Cusack, R., & Lancaster, J. (2001). Using the talairach atlas with the MNI template. NeuroImage, 13, 85.

Burton, L., & Fogarty, G. J. (2003). The factor structure of visual imagery and spatial abilities. Intelligence, 31, 289-318.

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. Trends in Cognitive Sciences, 4, 215-222.

Buzaki, G. (2002). Theta oscillations in the hippocampus. Neuron, 33, 325-340. `

Carroll, J. B. (1993). Human Cognitive Abilities: A Survey of Factor-analytic Studies. New York: Cambridge University Press.

Casey, M. B., Pezaris, E., & Nuttall, R. L. (1992). Spatial ability as a predictor of math achievement: the importance of sex and handeness patterns. Neuropsychologia, 30, 35-40.

Choi, C. (2004). The effects of mental training with brain-wave bio-feedback on mental attention & energy substrates after maximal exercise. Journal of Sport and Leasure Studies, 21, 441-451.

Christopoulos, G. I., Tobler, P. N., Bossaerts, P., Dolan, R. J., & Schultz, W. (2009). Neural correlates of value, risk, and risk aversion contributing to decision making under risk. The Journal of Neuroscience, 29, 12574-12583.

Chung, B. (2007). Frontal brain asymmetry, positive affect and approach motivation. The Korean Journal of Experimental Psychology, 19, 127-147.

Chung, B. & Yoon, B. (2008). Frontal brain asymmetry and negative emotion regulation. The Korean Journal of Experimental Psychology, 20, 203-221.

Curran-Everett, D. (2018). Explorations in statistics: The log transformation. Advanced in Physiology Education, 42, 343-347.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. Journal of Experimental Psychology: General, 122, 371-396.

Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. Neuron, 56, 384–398.

Fairclough, S. H., Venables, L., & Tattersall, A. (2005). The influence of task demand and learning on the psychophysiological response. International Journal of Psychophysiology, 56, 171-184.

Fehr, T., Code, C., & Herrmann, M. (2007). Common brain regions underlying different arithmetic operations as revealed by conjunct fMRI-BOLD activation. Brain research, 1172, 93–102.

Fitzgibbon, S. P., Pope, K. J., Mackenzie, L., Clark, C. R., & Willoughby, J. O. (2004). Cognitive tasks augment gamma EEG power. Clinical Neurophysiology, 115, 1802-1809.

Freeman, W. J., Burke, B. C., Holmes, M. D. (2003). Aperiodic phase re-setting in scalp EEG of beta-gamma oscillations by state transitions at alpha-theta rates. Human Brain Mapping, 19, 248-272.
Gersten, R., Jordan, N. C., & Jonathan, R. (2005). Early identification and interventions for students with mathematics difficulties. Journal of Learning Disabilities, 38, 293-304.
Guay, R. B. (1976). Purdue Spatial Visualization Test. West Lafayette, IN: Purdue Research Foundation.
Halari, R., Sharma, T., Hines, M., Andrew, C., Simmons, A., & Kumari, V. (2006). Comparable fMRI activity with differential behavioural performance on mental rotation and overt verbal fluency tasks in healthy men and women. Experimental Brain Research, 169, 1-14.
Hallez, H., Vanrumste, B., Grech, R., Muscat, J., De Clercq, W., Vergult, A., ... Lemahiu, I. (2007). Review on solving the forward problem in EEG source analysis. Journal of NeuroEngineering and Rehabilitation, 4, 46.
Hampshire, A., Chamberlain, S. R., Monti, M. M., Duncan, J., & Owen, A. M. (2010). The role of the right inferior frontal gyrus: inhibition and attentional control. Neuroimage, 50, 1313-1319.
Hartwigsen, G., Neef, N. E., Camilleri, J. A., Margulies, D. S., & Eickhoff, S. B. (2019). Functional segregation of the right inferior frontal gyrus: Evidence from coactivation-based parcellation. Cerebral Cortex, 29, 1532-1546.
Hawes, Z., Sokolowski, H. M., Ononye, C. B., & Ansari, D. (2019). Neural underpinnings of numerical and spatial cognition: An fMRI meta-analysis of brain regions associated with symbolic number, arithmetic, and mental rotation. Neuroscience and biobehavioral reviews, 103, 316–336.
Herrmann, C. S., Munk, M. H., Engel, A. K. (2004). Cognitive functions of gamma-band activity: memory match and utilization. Trends in Cognitive Sciences, 8, 347-355.
Hirata, M., Kato, A., Taniguchi, M., Saitoh, Y., Ninomiya, H., Ihara, A., Kishima, H., Oshino, S., Baba, T., Yorifuji, S., & Yoshimine, T. (2004). Determination of language dominance with synthetic aperture magnetometry: comparison with the Wada test. NeuroImage, 23, 46–53.
Ho, C.-H., Eastman, C. (2005). An investigation of 2D and 3D spatial and mathematical abilities. Design Studies, 27, 505-524.
Hope, J. & Sherrill, J. (1987). Characteristics of unskilled and skilled mental calculators. Journal for Research in Mathematics Education, 18, 98-111.
Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. Nature Reviews Neuroscience, 6, 435.
Hwang, T. (2012). The analysis of brain waves in response to linguistic stimuli to difference brain regions (Unpublished Doctoral Dissertation). Changwon National University, Gyeongnam, Republic of Korea.
Jasper, H. H. (1958). The ten-twenty electrode system of the international federation. Electroencephalography and Clinical Neurophysiology, 10, 371-375.
Jensen, E. (2007). Introduction to Brain-compatible Learning. Thousand Oaks, CA: Corwin Press.
Jeong, J. & Yun, S. (2008). The relative power spectral analysis of EEG activity during the inductive inquiry task performance with caminalcules. Biology Education, 36, 456-467.
Jessup, R. K., Busemeyer, J. R., & Brown, J. W. (2010). Error effects in anterior cingulate cortex reverse when error likelihood is high. The Journal of Neuroscience, 30, 3467-3472.
Jung, S., Ji, S., Lee, O., Kwak, R., & Lee, J. (2006). A study on the prefrontal EEG activities in the case of audio-visual learning using wavelet transform. Conference on the Korean Institute of Electrical Engineers, 2177-2178.
Kang, Y. (2015). Comparison of children’s social skills by brain exercise and neuro-feedback training with their learning abilities by EEG (Unpublished Doctoral Dissertation). University of Brain Education, Chungnam, Republic of Korea.

Kang, J., Gu, Y., Kwon, O., Kim, D., Kim, Y., Moon, J., ... Jung, K. (2017). Art and Application of EEG Analysis. Seoul: Medbook.

Kim, D., & Choi, C. (2001). Electroencephalogram. Seoul: Korea Medical Book Publishing Company.

Kim, D. W., Kim, M. S., Kim, S. P., Park, Y. M., Park, J. Y., Bae, K. Y., ... Hwang, H. J. (2017). Understanding and Application of EEG. Seoul: Hakjisa.

Kim, D. W., Kim, M. S., Kim, S. P., Park, Y. M., Park, J. Y., Bae, K. Y., ... Park, Y. O. (2017). Trends in Brain Wave Signal and Application Technology. Electronics and Telecommunications Trends, 33, 19-28.

Kim, E. & Shim, J. (2010). Effects of motivation activity in brain education on middle-school students' concentration and EEG activation. Journal of Brain Education, 3, 27-52.

Kim, S. & Jeong, J. (2010). Comparative analysis of hearing-impaired and non-disabled university students' brain waves measured during the biological classification and hypothesis-generation. Biology Education, 38, 621-630.

Kim, W. & Jin, S. (2005). LORETA analysis of EEG responding to positive/negative emotional stimuli for different sensitivities of behavioral activation and inhibition systems. Science of Emotion & Sensibility, 8, 403-413.

Kim, Y. M. (2013). Mathematical thinking, its neural system and implication for education. The Mathematical Education, 52, 19-41.

Kim, Y. Y., Lee, B., Shin, Y. W., Kown, J. S., & Kim, M. S. (2006). Activity of left inferior frontal gyrus related to word repetition effects: LORETA imaging with 128-channel EEG and individual MRI. NeuroImage, 29, 712-720.

Kim, Y. L. (2012). An exploratory study on the brain-based characteristics of students from Korea science academy of KAIST and from the general science focused high schools (Unpublished Doctoral Dissertation). Dongduk Women's University, Seoul, Republic of Korea.

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. Trends in Cognitive Sciences, 16, 606-617.

Ko, B. & Shim, J. (2012). Effects of brain development program for the youth on changes in EEG by brain areas depending on level of concentration and mental power. Youth Facilities and Environment, 10, 3-17.

Lachaux, J. P., Jung, J., Mainy, N., Dreher, J. C., Bertrand, O., Baciu, M., Minotti, L., Hoffmann, D., & Kahane, P. (2008). Silence is golden: transient neural deactivation in the prefrontal cortex during attentive reading. Cerebral Cortex, 18, 443–450.

Lee, S. (2021). Analysis of learners' cognitive learning activities using brain waves (Unpublished Doctoral Dissertation). Chungbuk National University, Chungbuk, Republic of Korea.

Lee, Y. (2009). Functional study of the human brain using MEG. Communications of the Korean Institute of Information Scientists and Engineers, 27, 50-57.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. Child Development, 56, 1479-1498.

McIntosh, A., Reys, B. J., & Reys, R. E. (1992). A proposed framework for examing basic number sense. For the Learning of Mathematics, 12, 2-8.

Michel, C. M., Murray, M. M., Lantz, G., Gonzalez, S., Spinelli, L., & Grave de Peralta, R. (2004). EEG source imaging. Clinical Neurophysiology, 115, 2195-2222.

National Council of Teachers of Mathematics (1989). Curriculum and Evaluation Standards for School Mathematics. Reston, VA: NCTM.

Ng, V. W., Bullmore, E. T., de Zubicaray G. I., Cooper, A., Suckling, J., & Williams, S. C. (2001). Identifying rate-limiting nodes in large-scale cortical networks for visuospatial processing: An illustration using fMRI. Journal of Cognitive Neuroscience, 13, 537-545.

Nichols, T. E. & Holmes, A. P. (2001). Nonparametric permutation tests for functional neuroimaging: A primer with examples. Human Brain Mapping, 15, 1-25.

Nieder, A. (2019). A Brain for Numbers. Cambridge, MA: The MIT Press.

Nikolaev, A. R., & Anokhin, A. P. (1998). EEG frequency ranges during perception and mental rotation of two- and three-dimensional objects. Neuroscience and Behavioral Physiology, 28, 670–677.

O'Keefe, J., Recce, M. L. (1993). Phase relationship between hippocampal place units and the EEG theta rhythm. Hippocampus, 3, 317-330.

Pang, J. (2005). A study on the computation and number-sense ability of elementary school students. Journal of the Korean School Mathematics Society, 8, 423-444.

Park, K. & Goo, J. (2007). A study of evaluating VR learning styles on user attention and memory. The KIPS Transactions: Part B, 14, 119-126.

Park, S. S. (2012). Validation of Korean version of the Revised PSVT:R (Purdue Spatial Visualization Tests: Visualization of Rotations). Korean Journal of Teacher Education, 28, 143-163.

Pascual-Marqui, R. D., Michel, C. M., & Lehmann, D. (1994). Low resolution electromagnetic tomography: a new method for localizing electrical activity in the brain. International Journal of Psychophysiology, 18, 49-65.

Pascual-Marqui, R. D. (1999). Review of methods for solving the EEG inverse problem. International Journal of Bioelectromagnetism, 1, 75-86.

Pascual-Marqui, R. D. (2002). Standardized low resolution brain electromagnetic tomography (sLORETA): Technical details. Methods and Findings in Experimental and Clinical Pharmacolgy, 24, 5-12.

Pascual-Marqui, R. D. (2009). Theory of the EEG inverse problem. In S. Tong & N. V. Thakor (Eds.), Quantitative EEG Analysis Methods and Clinical Applications (pp. 121-140). Boston, MA: Artech House.

Paus T. (2001). Primate anterior cingulate cortex: where motor control, drive and cognition interface. Nature reviews. Neuroscience, 2, 417–424.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. Annual Review of Neuroscience, 13, 25-42.

Reys, R., Reys, B., McIntosh, A., Emanuelsson, G., Johansson, B., & Yang, D.C. (1999). Assessing number sense of students in Australia, Sweden, Taiwan, and the United States. School Science and Mathematics, 99, 61-70.

Simonoff, J. S. (1996). Smoothing Methods in Statistics. New York, NY: Springer-Verlag.

Slotnick, S. D. (2021). Cognitive Neuroscience of Memory. Seoul: PYMATE.

Soltanlou, M., Artemenko, C., Dresler, T., Haeussinger, F. B., Fallgatter, A. J., Ehlis, A., & Nuerk, H. (2017). Increased arithmetic complexity is associated with domain-general but not domain-specific magnitude processing in children: A simultaneous fNIRS-EEG study. Cognitive, Affective, & Behavioral Neuroscience, 17, 724-736.

Sousa, D. A. (2009). How the Spacial Needs Brain Learns. Seoul: Sigma Press.

Sowder, J. T. (1992). Estimation and number sense. In D. A. Grouws (Ed.), Handbook of Research on Mathematics Teaching and Learning (pp.371-389). New York: Macmillan.

Tartre, L. A. (1990). Spatial skills, gender & mathematics. In E. Fennema & G. Leder (Eds.), Mathematics and Gender: Influences on Teachers and Students (pp. 27-59). New York: Teachers' College Press.

Thomas, M., Dalecki, M., & Abeln, V. (2013). EEG coherence during mental rotation of letters, hands and scenes. International Journal of Psychophysiology: Official Journal of The International Organization of Psychophysiology, 89, 128–135.

Titterington, D. M. (1985). Common structure of smoothing techniques in statistics. International Statistical Review, 53, 141-170.
Uddin, L. Q., Nomi, J. S., Hébert-Seropian, B., Ghaziri, J., & Boucher, O. (2017). Structure and function of the human insula. Journal of Clinical Neurophysiology, 34, 300-306.
Walsh V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. Trends in Cognitive Sciences, 7, 483–488.
Yoon, S. Y. (2011). Psychometric properties of the Revised Purdue Spatial Visualization Tests: Visualization of Rotations (The Revised PSVT:R) (Unpublished Doctoral Dissertation), Purdue University, Indiana, USA.
Young, J. D., Taylor, E. (1998). Meditation as a voluntary hypometabolic state of biological estivation. Physiology Published, 13, 149-153.
Zhang, X., & Lin, D. (2017). Does growth rate in spatial ability matter in predicting early arithmetic competence? Learning and Instruction, 49, 232–241.

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