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RESEARCH ARTICLE

Brain Imaging in Mathematics Education: An Analysis of KCI Studies

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뇌 영상기법을 활용한 수학 교육 연구 분석: 국내 KCI연구 중심으로

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ABSTRACT

This study reviews the application of EEG, fMRI, and fNIRS in mathematics education research in South Korea, analyzing 16 significant papers from the last 25 years. The results demonstrate a significant relationship between brainwave patterns and various aspects of mathematical learning. EEG studies highlighted the role of different brainwaves in math anxiety, computation, and problem-solving. fMRI research revealed the importance of whole brain activation in spatial and numerical processing. Studies using fNIRS emphasized the prefrontal cortex's involvement in mathematical tasks, particularly in spatial and computational tasks. Conclusions highlight the need for math learning programs that enhance brain connectivity and consider problem difficulty and learner preferences. The study advocates for more research on the prefrontal cortex, particularly in relation to math anxiety, and emphasizes the importance of brain imaging techniques in understanding cognitive processes in math education, suggesting an integrated approach in future research.

Key words: Mathematical education, brain imaging techniques, EEG, fMIR, fNIRS

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Introduction

The human brain utilizes numerical and spatial senses, language, long-term and working memory for mathematical thought, conducting complex processes like abstraction and reasoning (Kim, 2016). Understanding learners' thought processes in math education aids in identifying their difficulties and the underlying reasons. Consequently, research to comprehend differences in individual cognitive abilities, psychological states, and learning methods for developing personalized education strategies has been robust.

Post-1990s, with the evolution of brain imaging technology, a deeper understanding of the brain's anatomical structure and operational mechanisms has been achieved. This led to the rise of interdisciplinary fields such as 'numerical cognition' or 'mathematical cognition' (Arsalidou et al., 2017). These fields explore how the brain represents numbers and mathematical calculations, the foundation of mathematical abilities, and the factors influencing arithmetic learning. Additionally, various neurological techniques are being used to understand the biological basis of mathematical knowledge and uncover the essence of high-level thinking and mathematical inspiration.

Brain imaging studies have shown specific neuronal-level changes associated with mathematical experience, learning, and development. This has allowed for the scientific validation of concepts that were previously only theoretical in learning psychology and epistemology. This approach is expected to clarify previously undetected cognitive processes and contribute to more effective learning methods and curriculum design (Flobakk, 2015).

The brain plays a key role in regulating and supporting activities related to math learning, which demands abstract concepts and logical thinking. Researchers have been exploring the brain functions associated with math learning, shedding light on their interconnection.

Dehaene et al. (2004) studied brain activation patterns during various mathematical operations to identify relevant brain regions. Rosenberg et al. (2011) examined brain structure and activity changes during the math learning processes in elementary students. These studies help in understanding and addressing the challenges faced by children with difficulties in math learning.

The emergence of brain cognitive science studies related to psychology (Cozolino, 2013; Hook & Farah, 2013; Krishnan & Carey, 2013) has led to numerous investigations into how math anxiety impacts math learning through brain activity (Suárez-Pellicioni et al., 2013). The close relationship between brain function and math learning has become more evident, and research to elucidate their mechanisms is accelerating with advancements in brain imaging technology.

This study aims to review research applying brain imaging techniques like EEG, fMRI, and fNIRS to math education in South Korea. It seeks to illuminate current research trends based on thorough reviews of prior studies and explore implications for future research directions to enhance math education.

Theoretical Background

EEG

Electroencephalography (EEG) is a non-invasive technique for recording brain activity, using electrodes on the scalp to measure electrical signals. These brainwaves, varying in frequency, correspond to different brain states. Generally, delta waves (0.5-4Hz) are linked with deep sleep and unconscious functions. Theta waves (4-8Hz) are related to sleep, memory, learning, and crucial in processing new information. Alpha waves (8-12Hz), prevalent in a relaxed brain state, increase during rest with closed eyes. SMR waves (12-15Hz) indicate a passive brain activity state and have been recently used in ADHD training due to their association with attention deficits. Beta waves (13-30Hz) are linked to alert consciousness, planning, and thinking, and relate to neuromuscular activities. Gamma waves (over 30Hz) involve cognitive functions, memory, and problem-solving.

The data from EEG can be analyzed in various ways, such as Event-Related Potentials (ERP) for temporal changes in response to stimuli, or Power Spectrum analysis for examining frequency patterns. This technique is instrumental in both medical and psychological research, diagnosing conditions like epilepsy and Alzheimer's, and studying cognitive processes (Kanda et al, 2009).

EEG's real-time brain activity measurement is a major advantage, despite its lower spatial resolution and potential interference from physical barriers like hair or skin. Its growing use in math education research highlights its significance in understanding cognitive processes, making it a valuable tool to examine in the context of our country's research landscape.

fMRI

Functional Magnetic Resonance Imaging (fMRI) detects brain activity by measuring blood flow changes. Increased brain activity boosts blood supply to the active region, altering the magnetic properties of hemoglobin, which fMRI captures to map brain activity. fMRI visualizes and measures blood flow particles using three types of magnetic fields, allowing high-resolution observation of brain activity. This technique identifies which brain regions are activated during specific math tasks or learning environments, helping to understand brain activity patterns related to mathematical performance.

fMRI provides high-resolution 3D spatial images of brain activity, enabling observation of activity patterns in various brain areas with precise localization. However, its temporal resolution is slower compared to EEG, taking several seconds to detect changes, thus limiting its ability to capture rapid brain activity shifts. Additionally, the immobility of fMRI equipment and the requirement for subjects to be in a supine position make it challenging to measure brain activity during diverse educational activities. People with internal metal devices, like dental braces, cannot participate in fMRI studies. Despite these limitations, fMRI's spatial resolution advantage makes it a valuable tool in research aimed at pinpointing brain activation locations in math education, necessitating exploration of its methods and directions in research.

fNIRS

Functional Near-Infrared Spectroscopy (fNIRS) utilizes the absorption spectrum of hemoglobin molecules in the blood vessels near the brain's surface. It tracks brain activity by measuring the different light absorption characteristics of hemoglobin when it binds to and releases oxygen (Wilcox & Biondi, 2015). fNIRS equipment uses various fibers or lasers to project light onto the brain's surface. This light, absorbed and emitted based on oxygen consumption and blood flow changes in the brain tissue, is recorded to analyze brain activity patterns.

fNIRS is suitable for detecting brain activity in relatively shallow regions, up to 1-3 cm into the brain's surface. While it has a lower spatial resolution compared to high-resolution MRI or PET scans, it can track activity in specific brain areas. In terms of temporal resolution, fNIRS is superior to fMRI, making it well-suited for detecting rapid changes in brain activity, and can measure brain activity patterns on a second-by-second basis. It is also more portable than other brain imaging equipment and allows for a wider variety of tasks to be presented during studies. The growing application of fNIRS in math education research for observing brain dynamics and understanding students' math comprehension marks a pivotal moment in guiding future research directions in this field.

Literature Research Method

This study conducted a literature search using the Korean Citation Index (KCI), Korean Studies Information Service System (KISS), and Research Information Sharing Service (RISS) databases. We searched for papers published in the last 25 years (as of May 31, 2023), focusing on studies that used neuroscience techniques in math learning. A combination of keywords related to brain imaging techniques (brain, brainwaves, brain-based, brain imaging, fMRI, fNIRS, EEG, PET) and math learning (number, numeracy, mathematics) were used. A refined search within the results was then performed to specifically identify papers related to both the brain and mathematics. Out of the 300 papers initially identified, duplicates and studies not involving human subjects were excluded, resulting in a selection of 16 relevant papers. Fig. 1 illustrates the detailed search process, while Table 1 outlines the general characteristics of the final selected papers.

The 16 papers ultimately selected were conducted between 2009 and 2022. From a technical perspective, 10 papers used EEG, 3 used fMRI, and 3 applied fNIRS. In terms of topics, numerical sense and computation were the most common, and subjects related to spatial sense and math anxiety were also covered. The age of the research participants ranged widely from 7 to 75 years old.

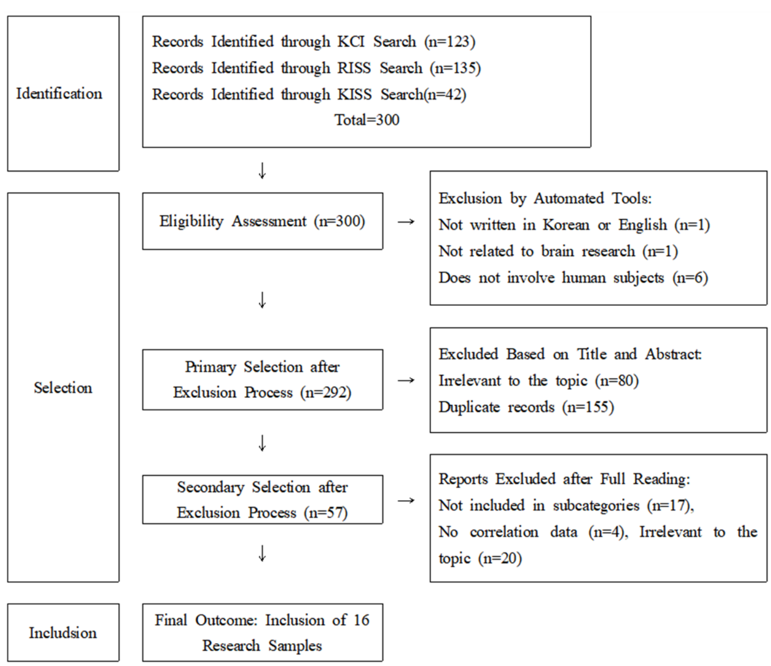

Fig. 1. Procedure for identifying target papers through literature search

Table 1. The List of Selected Studies

No.	Study	Technique	Domain		Sample size	age	Journal
			Cognition	Emotion			
1	Go (2009)	EEG	Arithmetic operations		1	75	Journal of the Korean School Mathematics Society
2	Kwon (2011)	EEG	Addition learning		21	7-13	Journal of The Korean Association of information Education
3	Kwon (2014)	EEG	Supported/ unsupported learning		24	19-25	Journal of The Korean Association of Information Education
4	Yun & Shin(2015)	EEG	Basic arithmetic operations	Math anxiety	22	12	Research in Mathematical Education
5	Go & Lee (2016)	EEG	Functions	Math anxiety	39	15	Mathematical Education
6	Han & Go(2016)	EEG	Functions Psychological treatment	Math anxiety	11	15-16	Journal of Educational Research in Mathematics
7	Kim (2018)	EEG	Numerical /word problems		12	Adult	Journal of Korea Society Educational Studies in Mathematics
8	Jung & Jang(2020)	EEG	Memorization/ procedural task	Preferred /non-preferred musical stimulus	12	19-23	The Journal of The Korea Institute of Electronic Communication Sciences
9	Kim (2019)	EEG	Numerical sense Spatial sense		20	19-23	Journal of Educational Research in Mathematics
10	Roh, Kim & Kwon (2022)	EEG	A math Class after a physical class		34	10	Brain, Digital & Learning
11	Yoon & Lee(2008)	fMRI	Linguistic / math achievement Verbal/spatial working memory		9	16	Journal of The Korean Data Analysis Society
12	Jo (2013)	fMRI	Problem-solving ability Problem-solving strategy		21	7-8	The Korean Journal of Cognitive and Biological Psychology
13	You, Bae, Ryoo, Park (2022)	fMRI		Preferred rectangular ratios	24	30	Journal of Communication Design
14	Min, Ahn, Lee & Son (2022)	fNIRS		Math anxiety	48	11-12	Brain, Digital & Learning
15	Yu, Ahn, Lee(2022)	fNIRS	Math achievement Preferred cognitive style		30	12	Brain, Digital & Learning
16	Kang(2021)	fNIRS	Transformational geometry program			20	Brain, Digital & Learning

Results

Technical Factors

EEG: Brain Waves

Out of 16 papers analyzed for brain activity, 10 utilized EEG, the most prevalent method in this study. EEG's distinction lies in measuring brainwaves through synaptic electrical impulses, differing from fMRI and fNIRS. Its high temporal resolution is advantageous for time-series analysis in experiments. The EEG-based studies focused on analyzing relative power spectra to identify significant brainwave activity and interpreted these in relation to brain function. They also analyzed the connectivity between different brain regions. Notable findings from domestic EEG research related to mathematics learning include.

Elderly learners (age 75) showed higher gamma wave activity in math activities connected to daily life (Go, 2009). Kwon (2011) examined the association between arithmetic learning, emotions, and brain hemispheres using implicit association tests. Simple calculations were more closely linked to emotions in the right parietal lobe, while complex calculations showed stronger associations with emotions in the left occipital lobe's SMR waves. For non-associated combinations, significant differences in beta waves were observed in the right temporal lobe. In Kwon (2014)'s study, when arithmetic learning was supported, alpha and SMR waves in the parietal lobe were significantly higher than in self-directed learning without support. Yun & Shin (2015) found that groups with high math anxiety had increased delta wave activity in the right frontal lobe. Go & Lee (2016) noted more significant changes in brainwaves when functions were represented graphically than when graphs were converted into functions, as revealed by ERP analysis. Han & Go (2016) observed that higher math anxiety correlated with greater brainwave potential differences. Kim (2018) analyzed brainwave changes when solving formulaic and word problems, finding increased theta and beta waves during word problem-solving. Kim (2019) also discovered that both numerical sense and spatial ability tasks elicited significantly higher beta waves in the right brain. Jung & Jang (2020) confirmed that solving math problems with preferred music resulted in higher average power compared to when listening to non-preferred music. After a physical education class, higher gamma waves in the right brain and lower alpha waves in the left brain were observed during subsequent math classes (Noh et al., 2022).

fMRI: Whole Brain Activation

fMRI, with its higher spatial resolution compared to EEG, offers the advantage of examining brain regions related to math activities more specifically. There were three studies that measured brain activation during math activities using fMRI in South Korea.

In the research by Yoon & Lee (2008), the parahippocampal gyrus (lateral hippocampus) was more activated in spatial working memory tasks, while the frontal lobe (superior frontal gyrus) was more active in vebal working memory tasks. For spatial memory tasks, students with higher math scores showed greater brain activation, and in verbal memory tasks, students with higher linguistic scores had more brain activation. Jo (2013) compared math problem-solving and brain activation changes over a year in second-grade elementary students. Significant activation changes in the hippocampus and surrounding areas were observed in students whose math problem-solving abilities improved significantly. Particularly, students who increased their memory retrieval strategies showed activation in the frontal-parietal network, including the medial temporal lobe. Students with improved problem-solving accuracy showed increased brain activity in areas such as the medial temporal lobe, bilateral visual cortex, and lateral occipito-temporal lobe. You et al. (2022) measured the hippocampal signal intensity in 24 adult men and women presented with rectangles of varying ratios. Both men and women showed the lowest average brain signal intensity for rectangles with golden ratios.

All three studies confirmed the hippocampus's involvement in math activities. The hippocampus, in conjunction with the medial temporal lobe, plays a crucial role in creating long-term declarative memory (Liu et al, 2004) and interacts with other regions in the process of storing and retrieving information, thus influencing most math activities (Kim , 2012). However, the analyzed studies showed differences in interpreting the activation of this region. Yoon & Lee (2008) found that students' hippocampi were more activated when solving tasks they were good at, while You et al. (2022) observed lower hippocampal activation when participants viewed rectangles with their preferred ratios.

fNIRS: Prefrontal Cortex

There were three domestic studies using fNIRS equipment, specifically the NIRSIT device (OBELAB inc.), to measure brain activity during math tasks. Unlike other fNIRS devices that measure the whole brain, NIRSIT is worn on the forehead, focusing on the prefrontal cortex but offering the advantage of easy wearability and mobility, suitable for various learning environments.

Kang (2021) conducted a transformational geometry program using tangrams for first graders, considering their geometric thinking levels. Before and after the program, brain activity and connectivity were analyzed. The DLPFC area was significantly activated in all tasks involving movement, rotation, and reflection. After the program, significant activation was observed in the VLPFC, DLPFC, and FPC areas, with enhanced functional connectivity between the left and right hemispheres. The DLPFC area showed increased connectivity with the opposite OFC area, and the left VLPFC area showed connectivity with both the right DLPFC and left OFC areas.

Yu et al. (2022) analyzed differences in brain activation based on learners' academic achievement in mathematics and preferred cognitive styles (visual, verbal) when presented with math problems in different formats (numeric, auditory, pictorial). The group with lower math achievement showed more activation in areas other than the DLPFC when solving unfamiliar auditory and pictorial math problems. No significant differences in brain activation were found for numeric problems. Conversely, learners with a visual cognitive style showed more activation in the DLPFC, FPC, and OFC areas when solving pictorial problems, but no differences were noted for numeric problems.

Min et al. (2022) developed an fNIRS-based math anxiety assessment tool to differentiate between groups with high and low math anxiety based on brain activation. During tasks involving arithmetic operations, the group with high math anxiety showed significantly lower activation in the bilateral DLPFC compared to the low anxiety group. The devised math anxiety assessment tool showed a significant correlation with traditional self-report questionnaires in the bilateral DLPFC and right OFC areas.

Cognitive Factors

Computation

Among the papers analyzed, eight specified mathematical ability in terms of numerical sense and computation skills. Kwon (2011) found that simple addition problems were more associated with emotions than logic, while complex addition problems were more associated with logic. Kwon (2014) reported that appropriate support in computational learning resulted in increased activation of alpha and SMR waves in the parietal lobe. Yun & Shin (2015) analyzed brain activity and connectivity in arithmetic operations, noting that students with low math anxiety solved math problems more quickly and accurately, showing active brain networks centered around the bilateral parietal lobes. Kim (2019) observed increased beta wave activity in the right parietal lobe when solving numerical sense-related problems. Min et al. (2022) developed an fNIRS-based math anxiety assessment tool and demonstrated its significant correlation with traditional assessment methods. Yu et al. (2022) highlighted differences in brain activation when fraction addition tasks were presented in numeric, pictorial, and auditory formats, with variations also seen based on preferred cognitive styles.

Spatial Ability

Research papers analyzing spatial sense included studies by Yoon & Lee (2008), Kim (2019), and Kang (2021). Yoon & Lee reported activation in the parahippocampal gyrus (lateral hippocampus) in spatial memory tasks, with higher math achievers showing more activation. Kim (2019) found increased beta wave activity in the right parietal lobe in spatial perception, mental rotation, and spatial visualization tasks. Kang (2021) observed significant activation in the DLPFC area in movement, rotation, and reflection tasks, with increased activation in the VLPFC, DLPFC, and FPC areas and strengthened functional connectivity between the left and right brain after a transformational geometry program.

Emotional Factors

Math Anxiety

Four papers in this study focused on math anxiety. Yun & Shin (2015) noted higher delta wave activity in the right frontal lobe in students with high math anxiety and identified four brain connectivity pathways in students with low math anxiety. Go & Lee (2016) analyzed accuracy, response time, and brainwaves in solving function problems, observing lower accuracy, longer response times, and inefficient brain usage in students with higher math anxiety. Han & Go (2016) designed a Brain-Integrated Education (BIE) program for alleviating math anxiety. They found reduced anxiety post-treatment, though the reduction factors varied by grade level, and high math anxiety was associated with higher brainwave amplitudes during function problem-solving. Min et al. (2022) developed an fNIRS-based math anxiety assessment tool, revealing a correlation between math anxiety and prefrontal cortex activity.

Preference

Three of the papers analyzed explored the relationship between personal preferences and brain activation in mathematical learning. Jung & Jang (2020) analyzed brainwave correlations when solving math problems with preferred or non-preferred music. They found higher theta wave power with preferred music, and the accuracy of problem-solving was higher with music than without. You et al. (2022) measured hippocampal signal intensity when presenting rectangles with various ratios, finding the lowest intensity with rectangles having a golden ratio (:1). Yu et al. (2022) observed higher prefrontal cortex activation when math problems were presented in learners' preferred cognitive styles.

Discussions

Technical Factors

EEG: Brain Waves

Brain Waves Synthesizing the results from the analyzed papers related to math learning and brainwaves, the following observations can be made.

Higher delta waves were observed in groups with high math anxiety, suggesting inefficiency in cognitive activities. Yun & Shin (2015) found increased delta waves in the right frontal lobe in high math anxiety groups. Delta waves, dominant during deep sleep, tend to decrease during difficult calculations (Pivik et al., Yu & Zhang, 2012; Micheloyannis et al., 2005). High delta waves in an awake state have been associated with brain disorders like epilepsy and mental retardation (Roland et al., 2013; Smith, 2005).

Theta wave activity was observed in tasks perceived as unfamiliar or difficult. Typically emerging just before sleep or during meditation, theta waves are highly related to working memory (Klimesch, 1999; Sauseng et al., 2004) and involved in episodic encoding and recall (Grabner & De Smedt, 2012; Ku et al., 2010). In math learning, they are associated with creative thinking and tend to increase when solving challenging problems (Gruzelier, 2014). Studies analyzed (Kim, 2018; Kwon, 2011) suggested increased theta activity in unfamiliar or sentence-based problems, indicating a need for more creative thinking.

Alpha wave activity in math learning can either facilitate or hinder learning. Alpha waves, typically appearing in a relaxed state, decrease during attention-demanding tasks while beta waves increase (Fernadez et al., 1995). Noh et al. (2021) found lower alpha and higher gamma waves after a physical education class, suggesting increased attention and arousal. Generally, increased alpha waves during rest and decreased during tasks are known to positively affect cognitive task performance (Hanslmayr et al., 2011). Conversely, studies show increased alpha waves are associated with improved concentration and learning ability (Tjoa, 1975), and lower math anxiety (Egner & Gruzelier, 2001; Wilson,1993), indicating varied interpretations based on the environment. Kwon (2014) interpreted increased alpha waves in supported arithmetic learning as indicating a relaxed state of concentration.

SMR waves, active in a stable brain state, are receiving attention for their relation to attention. They are used in research and neurofeedback training for attention-related brain disorders like ADHD (Barbosa & Cubo, 2021; Markiewicz, 2017). Kwon (2014) found strong SMR waves in supported arithmetic learning, suggesting a positive learning state.

Beta waves, appearing during intense concentration, were higher in sentence-based than formulaic problems (Kim, 2018) and showed significant right-side activation in both numerical sense and spatial ability tasks (Kim, 2019).

Gamma waves, occurring in comprehensive mental tasks or tense states, were higher in solving real-life related math problems and after physical exercise (Go, 2009; Noh et al., 2021). This aligns with findings that gamma waves activate during the use and integration of various senses and cognitive functions (Khana, 2006).

fMRI: Whole Brain Activation

Yoon & Lee (2008) interpreted higher activity in the left brain for spatial memory tasks and the right brain for verbal memory tasks in linguistically superior groups as an effect of 'neural efficiency,' where less brain activation occurs in areas responsible for specific superior intelligences.

In contrast, Jo (2013) found that improvement in mathematical problem-solving abilities in younger elementary students was related to activation in the bilateral visual cortex, emphasizing its importance. This area, which rapidly perceives and recognizes visual stimuli, showed increased activity in Rosenberg et al. (2011)'s study of 2nd and 3rd graders. This suggests that as students grow, faster recognition of numbers and formulas aids in problem-solving (Allison et al., 1994; Reinke et al., 2008). Interpretations of brain activation should be approached with caution and paralleled with other performance observations.

fNIRS: Prefrontal Cortex

All three studies using fNIRS found differences in the DLPFC area among groups. The DLPFC is involved in information processing, attention, and spatial information updating, remembering the location of objects (McLaughlin et al., 2009). Kang (2021)'s study confirmed DLPFC involvement in spatial tasks and strengthened connectivity with VLPFC and OFC as spatial abilities developed. Yu et al. (2022) also found significant DLPFC activation in the group preferring visual cognitive style when problems were presented pictorially. Moreover, higher math anxiety correlated with lower DLPFC activation during arithmetic problem-solving. These results indicate that the DLPFC is involved in solving math problems related to space and vision and is organically used with the OFC area, which is associated with emotions (Gray et al., 2002).

All three studies targeted elementary students and expanded the scope of tasks. However, they also share a limitation of using STROOP tasks (computer-presented tasks). As research with this technology is more recent, more studies are expected in the future.

Cognitive Factors

Computation

Research by Kwon (2014), Yun & Shin (2015), and Kim (2019) reaffirmed the close relationship between computational functions and the parietal lobe. This aligns with previous findings that the parietal lobe is involved in visually perceiving and processing computations and that spatial recognition plays a key role in computation (Hinault & Lemaire, 2016; Wirebring et al., 2015; Zamarian et al., 2009). However, differences in waveforms and active areas were noted depending on variables. Kwon (2011) found that easy addition problems were more closely associated with emotions than logic, while difficult ones were more logically aligned. Kwon(2014) noted that alpha and SMR waves in the parietal lobe were activated when appropriate support was provided in computational learning. Min et al. (2022) highlighted differences in prefrontal cortex activation between groups with high and low math anxiety during arithmetic tasks using fNIRS. Yu et al. (2022) showed differences in brain activation depending on the format of fraction addition tasks and preferred cognitive styles. The analyzed studies suggest that even the same computational tasks can lead to different brain activations depending on difficulty, support, math anxiety, and the format of the problem, indicating the need to consider various factors in computational learning.

Spatial Ability

Traditionally, spatial sense has been perceived as highly related to the right brain (Nadel & Hardt, 2004). Kim (2019) also found high activation of beta waves in the right brain in spatial sense tasks. However, Yoon & Lee (2008) reported that while high math achievers used the right brain more actively in spatial tasks, linguistically superior groups used the left brain more actively, consistent with other studies indicating individual differences due to brain hemisphere dominance (Hawes & Ansari, 2020). Kang Minjung (2021) found that spatial task performance involved the DLPFC and that spatial abilities developed with strengthened connectivity with the VLPFC and OFC. These findings suggest that enhanced functional connectivity between the left and right brain leads to the development of spatial sense (Sharma et al., 2017).

Emotional Factors

Math Anxiety

The studies analyzed showed a negative correlation between math problem-solving and brain inefficiency. Go & Lee (2016), Han & Go (2016) found large differences in brainwave potentials in groups with high math anxiety. This aligns with longstanding research associating math anxiety with brain activation (Maloney & Retanal, 2020; Ashcraft & Kirk ,2001) and indicates higher working memory usage (Ramirez et al., 2013). Yun & Shin (2015) noted differences in delta wave activation between groups with high and low math anxiety. Such brain activation patterns resemble those occurring in physical pain like headaches (Lyons & Beilock, 2012), suggesting math anxiety can be a psychological and physical burden. Additionally, studies repeatedly revealed the negative impact of math anxiety on DLPFC activation in the prefrontal cortex. Yun & Shin (2015) and Min et al. (2022) highlighted the high relevance of DLPFC, which governs working memory, to math anxiety (Vukovic et al, 2013). Furthermore, functional connectivity between brain areas centered around the DLPFC was more active in groups with low math anxiety. International research also consistently reports the negative impact of math anxiety on working memory and the importance of its alleviation (Gathercole & Alloway, 2008). Min et al. (2022) suggested the possibility of distinguishing math anxiety based on specific prefrontal cortex activation, implying that brain imaging techniques could directly aid in preventing and treating math anxiety.

Preference

Interpretations of the psychological impact of brain activation varied among studies. Jung & Jang (2020) interpreted higher brain activation while solving math problems with preferred music as an attention-enhancing effect of music. In contrast, Yu Jaesang et al. (2022) found that participants preferred shapes that showed the lowest brain activation. International studies have reported higher performance in tasks presented in preferred colors, with significant correlations in the precuneus cortex (Racey et al., 2019), and lower brain activation in preferred reading strategies, suggesting that preferred methods require less neural resources (Dong et al., 2022). The influence of personal preference should not be interpreted independently but seen as varying with the task environment.

Conclusions

The insights gained from analyzing 16 studies are as follows.

Firstly, there is a need for the development and effectiveness verification of math learning programs that can enhance brain connectivity. Many studies analyzed in this research showed that better math performance is associated with strengthened brain connectivity (Jo, 2013; Kang, 2021; Yun & SHIN, 2015). Despite numerous studies on mathematical functions and brain regions, drawing implications for math education from brain activation alone is challenging due to complex factors at play. Based on these studies, there's a need for programs enhancing brain connectivity across various mathematical areas, and their effectiveness should be verified using brain imaging technology.

Secondly, when using brain activation differences in math activities as a research focus, the complexity of the problems must be carefully considered. The studies analyzed showed that problem difficulty had a greater impact on brain activation than problem type or preference. Many studies discovered differences in brain activation due to problem difficulty even with the same preference or problem type. Psychological and cognitive factors organically influence each other, making it difficult to observe them separately. In the reviewed studies, lower brain activation was sometimes interpreted as a state of psychological comfort, while higher activation was seen as a positive emotional response. Yu et al. (2021)'s study also found that while preferred math problems showed more brain activation, familiar or easy problems did not show significant differences. Therefore, in brain imaging measurements related to math learning, problem difficulty itself can be a significant variable, requiring verification that the problems are of equal difficulty for accurate comparison.

Thirdly, more research is needed on the prefrontal cortex, particularly for the prevention and treatment of math anxiety. Studies on brain activation and math anxiety are being actively conducted in South Korea. All analyzed papers significantly highlighted the differences in brain activation due to math anxiety, focusing on the prefrontal cortex, especially the DLPFC area. Based on these results, more research directly implying the alleviation of math anxiety is necessary. As many previous studies have suggested its possibility, programs that can be used for the prevention and treatment of math anxiety through brain measurements could be highly useful in educational settings.

Recommendations

Based on the analysis of 16 studies on mathematics and brain imaging techniques, the following recommendations are briefly presented. Firstly, more active brain research related to math education is needed. More than half of the analyzed papers (10 out of 16) were published in journals not directly related to math education but related to information, communication, psychology, and brain-based education. There were no papers on fMRI and fNIRS in math education-related journals.

Secondly, research with sufficiently large sample sizes is needed. The average sample size in the analyzed studies was 21, with group-based studies involving around 10 participants. Due to this, some of the results mentioned in this paper did not achieve statistical significance. The difficulty of recruiting participants and the limitations in using equipment mean that individual research efforts are challenging, necessitating national-level support.

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