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Neurocognitive Approaches to Fraction Learning: Integrating EEG, fMRI, and Eye Tracking in Mathematics Education

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Abstract—**This paper reviews neurocognitive studies using EEG, fMRI, and eye-tracking to investigate how learners understand fractions. While challenges with fractions are well documented, most research has focused on adults, leaving children underrepresented. The review highlights how the brain processes symbolic and nonsymbolic fractions, the involvement of regions such as the intraparietal sulcus, and the role of visual attention and neural timing in mathematical reasoning. It also examines how targeted instruction can reshape brain activity related to fraction magnitude estimation. Emphasis is placed on the promise of portable EEG devices for real-time classroom use, supporting personalized and responsive teaching. The findings underscore the potential of educational neuroscience to inform more effective and developmentally appropriate practices in mathematics education.**

Index Terms—**educational neuroscience, fractions, EEG, fMRI, eye tracking, mathematical cognition, precision education.**

I. Introduction

EDUCATIONAL neuroscience has emerged at the intersection of psychology, neurology, and pedagogy, aiming to deepen our understanding of how individuals learn while also contributing to the refinement of teaching methods and learning environments. Despite the considerable body of research developed since the early 20th century, difficulties in mathematical understanding persist across age groups, affecting both children and adults [1]. Drawing on expertise from psychology, neuroscience, and education, recent research applies neuroscientific tools and experimental methodologies to address fundamental challenges in learning and instruction. As an interdisciplinary field, educational neuroscience enriches educational research by introducing innovative techniques that can inform more effective teaching practices and foster optimized learning environments. Technologies such as magnetic resonance imaging (MRI), electroencephalography (EEG), and near-infrared spectroscopy, alongside eye-tracking systems, facial expression analysis, and wearable devices like smartwatches, provide access to neurophysiological data under naturalistic conditions. These tools also support the identification of digital biomarkers and contribute to a better understanding of memory mechanisms [2].

In parallel, data mining techniques offer valuable insights into cognitive processes, behavioral patterns, and the factors influencing academic performance [3,4]. Such analyses facilitate the development of personalized learning strategies tailored to individual needs and learning profiles [5]. Neuroimaging studies have further enhanced this effort by identifying brain regions involved in understanding mathematical constructs like fractions, thereby providing a foundation for more targeted instructional design [6,7]. While neuroscience may not yield directly applicable classroom strategies, it can inform educational practice by integrating knowledge about brain function and cognitive development into pedagogical contexts [8,9]. It can also assist teachers in selecting instructional methods aligned with student characteristics and adapting their practices based on learners' cognitive profiles [10].

This evolving dialogue between educational research and cognitive neuroscience points to a dynamic, reciprocal relationship. Both disciplines contribute to a broader methodological framework aimed at shaping a new educational paradigm, where insights from neuroscience on brain development are actively used to enhance and enrich pedagogical practices [11]. Against this backdrop, the present paper synthesizes empirical findings from studies using EEG, fMRI, and eye-tracking technologies to uncover key neurocognitive patterns in mathematical thinking, with a specific focus on fraction understanding. By combining these complementary approaches, the paper aims to illuminate how the brain processes mathematical concepts and to explore how this knowledge can inform the creation of developmentally appropriate and cognitively attuned instructional strategies in mathematics education.

II. Neural Foundations of Mathematical Skills

Mathematical cognition is supported by a complex neural architecture involving multiple brain regions. Among these, the parietal cortex plays a central role. Specifically, mathematical tasks activate areas within and around the horizontal intraparietal sulcus (IPS), which has been consistently implicated in number processing [12, 13, 14]. Neuropsychological models suggest that numerical concepts are represented bilaterally, within cortical regions surrounding the IPS, using symbolic formats [15]. While the left parietal regions are primarily involved in quantity estimation regardless of format, the right parietal cortex appears to specialize in the processing of non-symbolic numerical information. These findings point to the existence of two functionally distinct but overlapping neural systems involved in mathematical cognition [16]. Importantly, IPS activation is not uniform across tasks. Studies have shown that it varies inversely with numerical distance; the closer two numbers are, the greater the activation observed in this region [17, 18].

In addition to the parietal cortex, the prefrontal cortex (PFC) also plays a key role in mathematical thinking, including even simple arithmetic tasks [16, 19]. The fronto-parietal network is thus considered essential for mathematical reasoning [20, 21]. Within this system, algebra and arithmetic both activate bilateral parietal areas but rely on distinct cognitive systems: algebra is more strongly associated with semantic networks, while arithmetic is linked to phonological and visuospatial processing [20].

Beyond these regions, additional cortical structures have been implicated in mathematical processing. These include the claustrum, the insula, and the cingulate gyrus, which contribute to broader executive and motivational processes [21]. The insula, in particular, appears to be crucial for children's mathematical computations, given its role in intrinsic motivation, emotional goal-setting, and attentional control [21]. Notably, increased activation in the insula has also been observed in adults and children when they face challenges in processing numerical magnitude [22]. Finally, mathematical error processing engages a distributed network including the anterior cingulate cortex (ACC), pre-supplementary motor area (pre-SMA), bilateral insula, thalamus, and the right inferior parietal lobule, regions associated with cognitive control, conflict monitoring, and attentional adjustment [23].

A. *Neurocognitive Data on Fraction Processing*

In recent years, research efforts have increasingly focused on understanding the cognitive mechanisms involved in the processing and acquisition of fractions. Studies have shown that symbolic representations of fractions are particularly challenging to comprehend and often lead to systematic errors. These difficulties are largely attributed to pre-existing cognitive biases that stem from the habitual use of whole number knowledge, observed in both children and adults. However, the specific stages of fraction perception and processing at which these difficulties arise remain unclear [24]. Despite growing interest in this area, investigations into the neurocognitive mechanisms underlying fraction processing are still relatively limited.

B. *Eye-Tracking Investigations in Fraction Processing*

One of the principal methods for exploring how learners process fractions is eye-tracking technology, which has been widely employed in research on mathematical cognition. It is an established tool in educational research, particularly in mathematics education [25, 26]. The most commonly used form of eye tracking relies on infrared light to non-invasively record eye movements and provide real-time data on visual attention and fixation points. This technique is grounded in the "eye–mind hypothesis" [27], which posits that eye movements reflect the ongoing cognitive processes of the viewer. As such, eye tracking offers insights into the problem-solving strategies employed by individuals when engaging with mathematical tasks [28], while also acknowledging certain methodological limitations related to interpretation and resolution [29].

A pioneering study by [30] examined how eight adults approached both simple and complex fraction comparison problems. Participants demonstrated flexible, problem-adapted strategies, adjusting their methods based on task complexity. Additionally, shorter fixation durations were observed for larger numerical ratios, supporting earlier findings on the relationship between numerical proximity and reaction time [31]. In contrast, [32] found that denominators attracted significantly more fixations than numerators, regardless of problem type—suggesting greater difficulty in processing denominators. Similarly, [33] reported that in complex fraction addition tasks with unlike denominators, participants exhibited increased fixations and saccades between denominators, indicating heightened cognitive demand.

Complementing these findings, [34] found that in fraction comparison tasks without shared elements, participants tended to focus more on numerators—likely reflecting an underlying natural number bias, where whole-number reasoning interferes with accurate fraction interpretation. Taken together, eye-tracking studies have made substantial contributions to our understanding of fraction processing. They have revealed how learners extract information from numerators and denominators and how they adjust their strategies based on the specific demands of each task. Moreover, findings indicate that participants frequently rely on simplified cognitive strategies or heuristics to navigate mathematical challenges, highlighting the role of intuitive reasoning in fraction understanding [24].

C. *Neuroimaging Studies of Fraction Processing: Insights from fMRI*

Over the past three decades, extensive research has been conducted on the neural correlates of whole number processing. In contrast, studies focusing on the neural mechanisms involved in the processing of fractions and proportional reasoning remain relatively scarce. Only a limited number of investigations have explored these mechanisms in adults using functional magnetic resonance imaging (fMRI). These studies have addressed various dimensions of fractional reasoning, including proportional comparisons [35, 36], the cognitive processing of fractions [38, 39, 35, 7, 37], and the influence of instructional interventions on neural activation patterns [6] .

Functional magnetic resonance imaging (fMRI) is a widely used non-invasive technique for evaluating brain activity, offering several key advantages. Its high spatial resolution enables the detailed mapping of small brain structures, allowing for comprehensive assessment of both cortical and subcortical regions. This makes fMRI particularly valuable for studying the distributed neural networks involved in mathematical cognition. However, its relatively limited temporal resolution, approximately two seconds to capture whole-brain activity, limits the ability to resolve rapid changes in neural processing. The inherent delay of the BOLD (blood-oxygen-level-dependent) signal further constrains the interpretation of fast, transient cognitive events. In the context of fraction-related tasks, where quick shifts in numerical comparison or proportional reasoning are crucial, these temporal limitations hinder a precise understanding of the timing and sequence of cognitive processes [24]. Neuroimaging findings have consistently identified the intraparietal sulcus (IPS) as playing a central role in the representation of both symbolic and nonsymbolic numerical magnitudes. Developmental neuroimaging studies in adults further support the IPS as a key hub for numerical cognition [19, 40].

[42] investigated how the neuronal recycling hypothesis may apply to the cognitive systems that process nonsymbolic fractions. They also examined how these systems could contribute to the development of abilities required for understanding symbolic fractions. Their study builds upon the theoretical framework of neuronal recycling proposed by [41], which suggests that the brain repurposes pre-existing cognitive systems—originally evolved for other purposes—to integrate culturally acquired concepts like symbolic fractions [42].

Building on these findings, [7] investigated the developmental trajectory of fraction understanding in school-aged children. They proposed that conceptual knowledge of fractions emerges gradually, beginning with an early sensitivity to nonsymbolic ratios—such as length comparisons—even before formal instruction. By Grade 2, children can interpret nonsymbolic proportions by drawing on innate magnitude perception skills, without using numerical symbols. By Grade 5, children develop the capacity to process symbolic fractions (e.g., 1/2, 3/4) through experience, engaging neural networks that were originally associated with nonsymbolic reasoning. This developmental shift supports the idea that symbolic fraction understanding builds upon earlier, magnitude-based representations.

In Grade 2, tasks involving nonsymbolic fraction comparisons were found to activate a neural network centered in the right ventral prefrontal cortex, including the right IPS and nearby prefrontal regions. By Grade 5, activation became more bilaterally distributed, engaging a broader ventral prefrontal network during both symbolic and nonsymbolic fraction tasks. This transition reflects a more integrated and efficient use of neural resources [7]. The IPS, a region critically involved in numerical cognition, is sensitive to the magnitude difference between fractions. It encodes proportional distance, thereby supporting both nonsymbolic and symbolic fraction processing. These findings underscore the brain's ability to reorganize existing cognitive systems to accommodate new mathematical concepts introduced through instruction [7].

[24] conducted a pioneering study to examine the effects of a structured educational intervention on the neural processing of fraction magnitudes in 48 adults. Over five consecutive days, participants engaged in a training program focused on estimating the placement of fractions on a number line ranging from 0 to 1. Each daily session included 96 tasks, with the possibility of up to 12 repetitions depending on individual performance. To assess changes in neural activation, participants performed symbolic fraction comparison tasks, line segment comparison tasks, and fraction-to-line matching tasks both before and after the intervention. Pre-training results showed that the numerical distance effect—a phenomenon in which smaller differences between numerical values require more cognitive effort—modulated IPS activity during line segment comparisons and fraction-to-line matching, but not during symbolic fraction comparisons. These findings indicate that symbolic fractions initially engaged distinct neural pathways compared to nonsymbolic magnitude tasks.

After the intervention, brain activation patterns for the non-symbolic tasks (line and line-to-fraction matching) remained stable. In contrast, symbolic fraction comparisons showed a marked change: the distance effect now influenced IPS activation, indicating that participants had started to engage magnitude-related neural resources when working with symbolic fractions. This shift suggests that training in numerical magnitude estimation may reshape neural processing and enhance fraction understanding at a conceptual level. Findings from fMRI studies underscore the complexity of fraction processing and its dynamic developmental trajectory. Research indicates that non-symbolic and symbolic fraction processing engages distinct yet partially overlapping neural mechanisms. Notably, [6] highlight the neuroplasticity of these systems, demonstrating how learning experiences can refine brain activity associated with mathematical skill development.

While fMRI provides valuable spatial insights into which brain regions are involved in fraction-related tasks, it lacks the temporal resolution needed to capture rapid neural processes occurring within milliseconds. This limitation makes it difficult to pinpoint the precise sequence of cognitive events during fast-paced tasks such as numerical comparisons or proportional reasoning. To overcome this challenge, researchers have increasingly adopted electroencephalography (EEG). With its high temporal resolution, EEG enables the real-time tracking of brain activity, making it especially suitable for exploring the fine-grained temporal dynamics of mathematical cognition. As a result, EEG complements fMRI by offering a more comprehensive understanding of how the brain processes complex concepts like fractions.

D. Investigating Fraction Perception Using EEG

Electroencephalography (EEG) is a non-invasive neuroimaging technique that records electrical activity along the scalp, capturing brain signals generated by neural oscillations with millisecond precision. Because of its high temporal resolution, EEG is particularly effective for studying mathematical cognition, offering valuable insights into the neural dynamics underpinning numerical reasoning and problem solving. For example, [43] demonstrated that EEG signals can reliably distinguish between verbal and mathematical cognitive processes, especially through variations observed in the theta frequency band. These findings underscore EEG's utility in detecting subtle distinctions in brain activity across different types of symbolic and domain-specific tasks, including arithmetic operations.

EEG-based research has advanced our understanding of the neural processes underlying mathematical thinking by revealing distinct patterns of brain activity associated with task complexity and type. Notably, studies by [44] & [45] have emphasized the role of the beta, gamma, and delta frequency bands in supporting cognitive effort, attentional control, and error detection during mathematical tasks. Additionally, [46] applied graph theory to EEG data and found that as mathematical tasks become more challenging, the brain organizes into more efficient and cohesive networks particularly within frontoparietal regions. These findings suggest that various mathematical processes, from simple arithmetic to complex reasoning, elicit distinct neural signatures that EEG can detect with high reliability.

While prior neuroimaging research has shown that processing fractions and decimals activates both shared and distinct brain regions, the precise timing of these processes remained poorly understood. [47] addressed this gap by employing Event-Related Potentials (ERPs) to examine the neural dynamics associated with fraction and decimal processing. Their study focused on comparing symbolic formats and investigating how numerical distance (i.e., whether numbers were numerically close or far apart) influenced ERP components such as P1/N1, P2, and N2.

The results revealed distinct ERP patterns for the two numerical formats. Decimal numbers elicited a larger N1 and a smaller P1 component in the parietal cortex compared to fractions. Moreover, the numerical distance effect significantly influenced the fronto-central P2 component for fractions, while a similar effect emerged in the left anterior N2 component for decimals. These patterns indicate that different cognitive systems are engaged in processing each format. Decimal recognition appears to rely more heavily on visual cortical areas, enabling faster and more efficient identification. Conversely, understanding fractions—which requires more elaborate cognitive operations—involves fronto-central brain regions responsible for fine-grained magnitude manipulation. The study also highlighted that these neural processing differences emerge within the first 100 milliseconds following stimulus presentation, demonstrating the importance of ERP techniques in capturing the rapid temporal dynamics of mathematical cognition.

[48] investigated the neural mechanisms underlying fraction understanding using EEG recordings in a sample of 24 adults engaged in fraction comparison tasks. Their results revealed distinct neural patterns, including longer reaction times for nonequivalent fractions and two specific ERP components: an early frontal N270 for nonequivalent fractions and a late parietal P300 for equivalent ones. These findings suggest that fraction processing involves cognitive operations similar to those used in arithmetic tasks, with nonequivalent fraction comparisons requiring greater cognitive effort and resource allocation. This study highlights the potential of ERP techniques in examining the temporal dynamics of fraction processing, offering valuable insights into the timing and sequence of brain activity during numerical reasoning.

In this context, [49] study was among the first to explore fraction learning processes through EEG in a school-aged population. A total of 512 fifth-grade students participated, of whom 44 (22 high-performing and 22 low-performing based on a diagnostic test on fractions) were selected for EEG recording during the execution of fraction-related tasks. High-performing students exhibited more balanced, bilateral theta band activation (4–7.5 Hz), in contrast to their low-performing peers, who showed greater reliance on the right hemisphere—particularly during the initial phases of problem solving. Moreover, in the beta1 frequency band (13–18 Hz), low-performing students demonstrated increased activity in the left hemisphere, especially when working on tasks involving discrete sets and area models. These findings suggest that high-performing students engage their brains more efficiently when processing fractions, drawing upon both hemispheres in a coordinated manner. Conversely, low-performing students appear to employ less effective cognitive strategies, resulting in greater cognitive effort and reduced efficiency in solving fraction problems. The differences in theta and beta1 activity highlight distinct neural processing patterns associated with performance levels and learning competence in fraction understanding.

III. Comparing Neuroimaging Methods (fMRI & EEG) in Fraction Processing and Educational Implications

Recent neuroimaging research has significantly advanced our understanding of the neural mechanisms underlying fraction comprehension. Functional Magnetic Resonance Imaging (fMRI), in particular, has been instrumental in identifying the brain regions involved in symbolic numerical processing. Numerous studies have demonstrated that the intraparietal sulcus (IPS) plays a central role in representing numerical magnitudes [19, 40, 14] . Moreover, the frontoparietal network has been shown to support complex arithmetic operations and proportional reasoning [35, 36, 38, 39, 7, 42, 6].

While fMRI offers crucial insights into the spatial organization of brain activity, its limited temporal resolution constrains our ability to capture the rapid neural processes that underlie numerical cognition [24]. To address this limitation, electroencephalography (EEG) has been proposed as a complementary method, offering millisecond-level temporal precision. Notably, studies using Event-Related Potentials (ERPs) have begun to uncover the temporal dynamics of processing different numerical formats, such as fractions and decimals, revealing distinct neural activation patterns and clear timing differences [47, 48]. EEG findings suggest that decimal numbers and fractions engage different cognitive and neural pathways. Decimal processing appears to rely mainly on visual brain areas, enabling faster and more automatic recognition. In contrast, fraction processing demands greater cognitive effort and engages fronto-central brain regions associated with complex and abstract numerical reasoning [47].

In support of this, [48] reported that comparisons involving nonequivalent fractions resulted in longer reaction times and increased brain activity, as reflected by the early frontal ERP component N270. Conversely, equivalent fractions were associated with the late parietal P300 component, linked to cognitive control and recognition of numerical relationships. These results suggest that fraction processing recruits neurocognitive mechanisms similar to those used in arithmetic operations, with nonequivalent comparisons requiring higher cognitive resource allocation. Despite substantial progress in understanding the neural underpinnings of fraction processing, a notable research gap remains regarding how these processes unfold in children. Most existing studies focus on adult participants and predominantly employ fMRI, leaving the developmental trajectory of mathematical thinking in childhood—a critical period for acquiring fraction knowledge—relatively underexplored. As [7] note, children's understanding of fractions evolves from an early sensitivity to nonsymbolic ratios into the ability to manipulate symbolic representations through structured educational experiences.

Utilizing EEG to investigate the neural basis of this developmental progression could provide valuable insights into how children's brains adapt during fraction learning. Furthermore, identifying the temporal characteristics of fraction processing may inform the design of educational interventions that align with the natural course of cognitive development in children. In conclusion, fMRI research has laid a strong foundation for elucidating the neural mechanisms of fraction processing, yet its limitations underscore the importance of further EEG-based studies—particularly involving elementary-aged learners. The combined application of fMRI and EEG can offer a more complete picture of the cognitive and neural systems underlying fraction comprehension. Future EEG research with children holds promise for informing evidence-based instructional practices aimed at improving the acquisition of mathematical concepts.

IV. Discussion and Proposals for Future Educational Research

The integration of neuroimaging tools such as functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) into educational research has significantly expanded the understanding of the cognitive processes that underpin learning, particularly in domains such as arithmetic reasoning and fraction comprehension [53]. These technologies allow for precise observation of brain activity and offer critical insights into how learners process mathematical content, with variations depending on symbolic representation, task complexity, and individual cognitive profiles. However, current research has predominantly centered on adult populations or older students, resulting in a notable gap in understanding how mathematical concepts are acquired during the early stages of education. The classroom, where foundational learning takes place, remains an underutilized setting for applying such neuroimaging techniques. Moreover, the practical challenges associated with traditional EEG setups have limited their deployment in real-world educational environments [53].

This gap is especially evident in the context of fraction learning—a core mathematical concept introduced in the primary school curriculum and one that is often associated with persistent difficulties for young learners. Investigating how children's brains respond to both symbolic and nonsymbolic representations of fractions can offer valuable direction for the design of early instructional strategies. Addressing this need calls for the use of portable, wireless EEG technologies, such as the Muse 2 headset, which offer improved ergonomics and feasibility for use in school settings. These devices make it possible to collect reliable neurocognitive data with minimal disruption to classroom activities. In doing so, researchers can gain real-time access to measures of cognitive engagement and mental fatigue, enabling the development of more accurate and responsive learner profiles.

This approach aligns with the broader vision of precision education, which aims to tailor instruction to the specific needs of each learner by leveraging objective neurophysiological indicators. The integration of affordable, user-friendly neurotechnologies into routine classroom practice holds the potential to transform mathematics education by informing the development of personalized interventions and promoting educational equity. EEG-derived data—including markers of attention, engagement, and cognitive fatigue—can support the design of individualized learning pathways that are responsive to each student's cognitive state [50, 51]. The use of portable EEG systems like the Muse 2 also allows for continuous, non-intrusive monitoring within everyday teaching contexts, ensuring that insights from neuroscience can be seamlessly embedded into educational practice [7, 52].

By extending neuroscience beyond the laboratory and into the classroom, educators and researchers can co-develop real-time, developmentally appropriate strategies to support young learners—especially those struggling with abstract mathematical concepts such as fractions. Future research should prioritize the inclusion of primary-aged students in neurocognitive investigations and explore how emerging neurotechnologies can be effectively employed to support mathematical learning from the earliest stages. Bridging the gap between neuroscience and education through accessible, classroom-compatible tools offers a promising path toward more equitable and personalized instruction. Aligning neurocognitive data with instructional design not only enhances fraction learning but also contributes to the creation of more inclusive and effective learning environments. Realizing this vision will require sustained interdisciplinary collaboration, continued investment in research, and a renewed commitment to reimagining mathematics education for the challenges of the twenty-first century.

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References

[1] M. I. Fandiño Pinilla, "Fractions: conceptual and didactic aspects," *Acta Didactica Universitatis Comenianae. Mathematics*, vol. 7, pp. 81–115, 2007.

[2] P. Giannopoulou, M. A. Papalaskari, and S. Doukakis, "Neuroeducation and computer programming: A review," in *GeNeDis 2018*, pp. 59–66. Springer, 2020. [Online]. Available: https://doi.org/10.1007/978-3-030-35249-3_8

[3] M. S. Schwarz, V. Hinesley, Z. Chang, and J. M. Dubinsky, "Neuroscience knowledge enriches pedagogical choices," *Teaching and Teacher Education*, vol. 83, pp. 87–98, Apr. 2019. [Online]. Available: https://doi.org/10.1016/j.tate.2019.04.002

[4] M. Tissenbaum and J. D. Slotta, "Data-driven iteration of a collaborative inquiry curriculum," *Journal of the Learning Sciences*, vol. 28, no. 1, pp. 84–126, 2019. [Online]. Available: https://doi.org/10.1080/10508406.2018.1522253

[5] W. Strielkowski, V. Grebennikova, A. Lisovskiy, G. Rakhimova, and T. Vasileva, "AI-driven adaptive learning for sustainable educational transformation," *Sustainable Development*, vol. 33, no. 2, pp. 1921–1947, 2025.

[6] S. M. Wortha, J. Bloechle, M. Ninaus, K. Kiili, A. Lindstedt, J. Bahnmueller, … E. Klein, "Neurofunctional plasticity in fraction learning: An fMRI training study," *Trends in Neuroscience and Education*, vol. 21, p. 100141, 2020.

[7] Y. Park, P. B. Kalra, Y. S. Chuang, J. V. Binzak, P. G. Matthews, and E. M. Hubbard, "Developmental changes in nonsymbolic and symbolic fractions processing: A cross-sectional fMRI study," *Developmental Science*, vol. 28, no. 5, p. e70042, 2025.

[8] Z. Chang, M. S. Schwartz, V. Hinesley, and J. M. Dubinsky, "Neuroscience concepts changed teachers' views of pedagogy and students," *Frontiers in Psychology*, vol. 12, p. 685856, 2021.

[9] M. S. Thomas, D. Ansari, and V. C. Knowland, "Annual research review: Educational neuroscience: Progress and prospects," *Journal of Child Psychology and Psychiatry*, vol. 60, no. 4, pp. 477–492, 2019

[10] P. Toscani, "Éditorial du dossier 'Neurosciences et éducation'," *Éducation et Socialisation. Les Cahiers du CERFEE*, no. 49, 2018.

[11] D. A. Turner, "Which part of 'two-way street' did you not understand? Redressing the balance of neuroscience and education," *Educational Research Review*, vol. 6, no. 3, pp. 224–232, 2011. [Online]. Available: https://doi.org/10.1016/j.edurev.2011.04.001

[12] S. Dehaene, M. Piazza, P. Pinel, and L. Cohen, "Three parietal circuits for number processing," in *The Handbook of Mathematical Cognition*, pp. 433–453. Psychology Press, 2005.

[13] M. Piazza and E. Eger, "Neural foundations and functional specificity of number representations," *Neuropsychologia*, vol. 83, pp. 257–273, 2016.

[14] M. Arsalidou, M. Pawliw-Levac, M. Sadeghi, and J. Pascual-Leone, "Brain areas associated with numbers and calculations in children: Meta-analyses of fMRI studies," *Developmental Cognitive Neuroscience*, vol. 30, pp. 239–250, 2018.

[15] D. Ansari, N. Garcia, E. Lucas, K. Hamon, and B. Dhital, "Neural correlates of symbolic number processing in children and adults," *Neuroreport*, vol. 16, no. 16, pp. 1769–1773, 2005.

[16] H. M. Sokolowski, W. Fias, A. Mousa, and D. Ansari, "Common and distinct brain regions in both parietal and frontal cortex support symbolic and nonsymbolic number processing in humans: A functional neuroimaging meta-analysis," *Neuroimage*, vol. 146, pp. 376–394, 2017.

[17] R. Cohen Kadosh, A. Henik, O. Rubinsten, H. Mohr, H. Dori, V. Van de Ven, *et al.*, "Are numbers special? The comparison systems of the human brain investigated by fMRI," *Neuropsychologia*, vol. 43, pp. 1238–1248, 2005.

[18] L. Kaufmann, S. E. Vogel, M. Starke, C. Kremser, M. Schocke, and G. Wood, "Developmental dyscalculia: compensatory mechanisms in left intraparietal regions in response to nonsymbolic magnitudes," *Behavioral and Brain Functions*, vol. 5, pp. 1–6, 2009.

[19] R. W. Emerson and J. F. Cantlon, "Continuity and change in children's numerical cognition," *Child Development Perspectives*, vol. 9, no. 3, pp. 152–156, 2015.

[20] Y.-L. Cheng, M. C. Cheung, C. S.-H. Ho, and T. K. Ng, "A systematic review of neuroimaging studies on mathematical processing," *Neuroscience & Biobehavioral Reviews*, vol. 132, pp. 556–572, 2022.

[21] M. Arsalidou, M. Pawliw-Levac, M. Sadeghi, and J. Pascual-Leone, "Brain areas associated with numbers and calculations in children: Meta-analyses of fMRI studies," *Developmental Cognitive Neuroscience*, vol. 30, pp. 239–250, 2018.

[22] G. Vatansever, S. Üstün, N. Ayyıldız, and M. Çiçek, "Developmental alterations of the numerical processing networks in the brain," *Brain and Cognition*, vol. 141, p. 105551, 2020.

[23] R. Hester, C. Fassbender, and H. Garavan, "Individual differences in error processing: a review and reanalysis of three event-related fMRI studies using the GO/NOGO task," *Cerebral Cortex*, vol. 14, no. 9, pp. 986–994, 2004.

[24] S. M. Wortha, A. Obersteiner, and T. Dresler, "Neurocognitive foundations of fraction processing," in *Handbook of Cognitive Mathematics*, pp. 1–27, 2021.

[25] M. L. Lai, M. J. Tsai, F. Y. Yang, C. Y. Hsu, T. C. Liu, S. W. Y. Lee, … C. C. Tsai, "A review of using eye-tracking technology in exploring learning from 2000 to 2012," *Educational Research Review*, vol. 10, pp. 90–115, 2013.

[26] A. R. Strohmaier, K. J. MacKay, A. Obersteiner, and K. M. Reiss, "Eye-tracking methodology in mathematics education research: A systematic literature review," *Educational Studies in Mathematics*, vol. 104, pp. 147–200, 2020.

[27] M. A. Just and P. A. Carpenter, "A theory of reading: from eye fixations to comprehension," *Psychological Review*, vol. 87, no. 4, p. 329, 1980.

[28] K. Holmqvist, M. Nyström, R. Andersson, R. Dewhurst, H. Jarodzka, and J. Van de Weijer, *Eye Tracking: A Comprehensive Guide to Methods and Measures*. Oxford, U.K.: OUP Oxford, 2011.

[29] M. Carrasco, "Visual attention: The past 25 years," *Vision Research*, vol. 51, no. 13, pp. 1484–1525, 2011.

[30] A. Obersteiner, G. Moll, J. T. Beitlich, C. Cui, M. Schmidt, T. Khmelivska, and K. Reiss, "Expert mathematicians' strategies for comparing the numerical values of fractions—Evidence from eye movements," *North American Chapter of the International Group for the Psychology of Mathematics Education*, 2014.

[31] A. Obersteiner and C. Tumpek, "Measuring fraction comparison strategies with eye-tracking," *ZDM*, vol. 48, pp. 255–266, 2016.

[32] S. Huber, K. Möller, and H. C. Nuerk, "Adaptive processing of fractions—Evidence from eye-tracking," *Acta Psychologica*, vol. 148, pp. 37–48, 2014.

[33] A. Obersteiner and I. Staudinger, "How the eyes add fractions: Adult eye movement patterns during fraction addition problems," *Journal of Numerical Cognition*, vol. 4, no. 2, pp. 317–336, 2018.

[34] M. Hurst and S. Cordes, "Rational-number comparison across notation: Fractions, decimals, and whole numbers," *Journal of Experimen-*

tal Psychology: Human Perception and Performance, vol. 42, no. 2, p. 281, 2016.

[35] S. N. Jacob and A. Nieder, "Tuning to non-symbolic proportions in the human frontoparietal cortex," *European Journal of Neuroscience*, vol. 30, no. 7, pp. 1432–1442, 2009.

[36] J. Mock, S. Huber, J. Bloechle, J. Bahnmueller, K. Moeller, and E. Klein, "Processing symbolic and non-symbolic proportions: Domain-specific numerical and domain-general processes in intraparietal cortex," *Brain Research*, vol. 1714, pp. 133–146, 2019.

[37] M. R. Lewis, P. G. Matthews, and E. M. Hubbard, "Neurocognitive architectures and the nonsymbolic foundations of fractions understanding," in *Development of Mathematical Cognition*, pp. 141–164. Elsevier, 2016.

[38] M. DeWolf, J. N. Chiang, M. Bassok, K. J. Holyoak, and M. M. Monti, "Neural representations of magnitude for natural and rational numbers," *NeuroImage*, vol. 141, pp. 304–312, 2016.

[39] A. Ischebeck, M. Schocke, and M. Delazer, "The processing and representation of fractions within the brain: An fMRI investigation," *NeuroImage*, vol. 47, no. 1, pp. 403–413, 2009.

[40] I. M. Lyons, H. C. Nuerk, and D. Ansari, "Rethinking the implications of numerical ratio effects for understanding the development of representational precision and numerical processing across formats," *Journal of Experimental Psychology: General*, vol. 144, no. 5, p. 1021, 2015.

[41] S. Dehaene and L. Cohen, "Cultural recycling of cortical maps," *Neuron*, vol. 56, no. 2, pp. 384–398, 2007.

[42] R. M. Lewis, L. K. Gibbons, E. Kazemi, and T. Lind, "Unwrapping students' ideas about fractions," *Teaching Children Mathematics*, vol. 22, no. 3, pp. 158–168, 2015.

[43] E. V. Chemerisova, M. S. Atanov, I. N. Mikheev, and O. V. Martynova, "Classification of verbal and mathematical mental operations based on the power spectral density of EEG," *Psychology*, vol. 15, no. 2, pp. 268–278, 2018.

[44] E. V. Chemerisova, M. S. Atanov, I. N. Mikheev, and O. V. Martynova, "Classification of verbal and mathematical mental operations based on the power spectral density of EEG," *Psychology*, vol. 15, no. 2, pp. 268–278, 2018.

[45] F. J. Alvarado-Rodríguez, K. P. Ibarra-González, C. Eccius-Wellmann, H. Vélez-Pérez, and R. Romo-Vázquez, "Electrophysiological brain response to error in solving mathematical tasks," *Mathematics*, vol. 10, no. 18, p. 3294, 2022.

[46] M. A. Klados, K. Kanatsouli, I. Antoniou, F. Babiloni, V. Tsirka, P. D. Bamidis, and S. Micheloyannis, "A graph theoretical approach to study the organization of the cortical networks during different mathematical tasks," *PLoS One*, vol. 8, no. 8, p. e71800, 2013.

[47] P. Lin, Y. Zhu, X. Zhou, Y. Bai, and H. Wang, "Neural dissociations between magnitude processing of fractions and decimals," in *2021 43rd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*, Nov. 2021, pp. 92–95. IEEE.

[48] B. Rivera and F. Soylu, "Incongruity in fraction verification elicits N270 and P300 ERP effects," *Neuropsychologia*, vol. 161, p. 108015, 2021.

[49] O. P. Hoon, "Neuroscience in mathematics: An electroencephalographic study on fraction learning," *Journal of Science and Mathematics Education in Southeast Asia*, vol. 25, no. 2, pp. 15–31, 2002.

[50] S. D'Urso, R. Luongo, and F. Sciarrone, "Enhancing educational outcomes through EEG-based cognitive indices and supervised machine learning: A methodological framework," in *2024 28th International Conference Information Visualisation (IV)*, Jul. 2024, pp. 1–6. IEEE.

[51] N. Kosmyna and P. Maes, "AttentivU: an EEG-based closed-loop biofeedback system for real-time monitoring and improvement of engagement for personalized learning," *Sensors*, vol. 19, no. 23, p. 5200, 2019.

[52] J. G. Cruz-Garza, J. A. Brantley, S. Nakagome, K. Kontson, M. Megjhani, D. Robleto, and J. L. Contreras-Vidal, "Deployment of mobile EEG technology in an art museum setting: Evaluation of signal quality and usability," *Frontiers in Human Neuroscience*, vol. 11, p. 527, 2017.

[53] E. Lekati and S. Doukakis, "Neuroeducation and mathematics: The formation of new educational practices," in *Worldwide Congress on Genetics, Geriatrics and Neurodegenerative Diseases Research*, Cham: Springer International Publishing, 2022, pp. 91–96