The Cognitive Neuroscience of Mathematical Learning: Bridging Brain Research and Classroom Practice

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Abstract
The systematic review is a synthesis of literature on the cognitive neuroscience of mathematical learning, which then analyses 645 identified papers, which are relevant yet it is a sample of 50 of the best articles, which constitutes the analytical core. The review also utilised extensive search strategy which converted general research queries into several specific search statements and gave 597 original candidate papers in scholarly databases. Another 58 articles were found by systematic backward and forward citation chaining leasing to a total candidate pool of 655 studies which were rigorously scored on relevance across the criterion of methodological quality, the fit of articles with the purpose of the research, and contribution to the knowledge base on mathematical cognition neuroscience. The statistical analysis of the literature indicated that 60 percent of the studies were conducted in the pattern of neural activation, and 30 of the studies in particular found distributed frontoparietal networks to be the centre of mathematical processing. Quantitative synthesis revealed that strategies of neuroscience-informed instruction, tested on 15 intervention studies, indicated that out of the 15 interventions, the measures of learning outcomes improvement had an effectiveness range of 70 to 92, but more specifically, the highest effectiveness rates were 85 and 88, respectively, of gesture-based instruction and integrated number sense tutoring. Comparison of individual differences in 25 studies showed that 68% of them had competence-related neural variance, 42% of them had studied the effects of mathematics anxiety, and 58% of them had wondered on the effects of working memory. Cultural and socioeconomic factors even though only been focused on in 20 percent of studies, showed serious modulatory influences on neural processing pathways. The geographic distribution report was significantly dominated by Western bias, with 76% neuroimaging studies taking place in North America and Europe, just 4% in sub-Saharan Africa and 6% in Latin America, strongly suggesting critical deficiencies in cultural representative neuroscience research and the need to expand cross-cultural neuroscience studies to come up with more generally applicable models of mathematical cognition.

Introduction

Cognitive neuroscience of mathematical learning has become one of the most dynamic and signification fields in educational research in recent decades providing unprecedented understanding of the way the human brain processes, stores and applies mathematical knowledge. It is a research area at the interface

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of neuroscience, cognitive psychology, and education, which utilises advanced neuroimaging tools and hip-hop experiment designs to discern the neurophysical bases of mathematical cognition found in various groups of people and across developmental levels. Since every one in five children around the world faces severe challenges with mathematics acquisition, and the consequences of this issue on academic performance, life chances, and societal economic engagement are immense, the neural mechanisms by which mathematics learning happens have become not only the focus of academic inquiry but an obligation to society (Demir-Lira et al., 2016; Looi et al., 2016). The combination of brain-based evidence and pedagogical practise is the potentially transformative aspect of overcoming achievement gaps in the cases of persistent differences in achieving results and ensuring optimal forms of instructional strategies in order to meet the requirements of all learners irrespective of their cognitive patterns and socioeconomic backgrounds. This synthesis is a paradigm shift of strictly behavioural perspectives on education to a broader comparative comprehension which encompasses not only the biological mechanisms of the learning process, but also the multifaceted interactions between the neural processes and environmental sources (Moore & Depue, 2016).

Although the neuroimaging techniques and our growing body of information on the brainbehaviour interaction have made tremendous contributions to the subject matter, stunning gaps still exist concerning how mathematical learning occurs at the neural level and how that information can be practically applied in a classroom setting. Although scholars have notably been able to point out key brain areas characterised by numerical processing such as intraparietal sulcus, angular gyrus as well as parts of the frontoparietal network, the dynamic interplay of these regions in the learning process has not been fully described yet (Wang et al., 2025; Xie et al., 2024; Ren and Libertus, 2023). Moreover, the discipline is faced by some basic questions related to the dissimilarities in neural activation processes across people, whether cultures and socioeconomic influences can have a role in the formation of mathematical cognition, and whether the neuroscientific discoveries in laboratories can be translated into the educational context on a real-life level. The extent and context of neuroscience application to education, along with scholars taking either a stance of concern in the prematureity of neuroscience translation and neurofable trading, or proclamations of being more aggressive with the integration of brain-based concepts into education continues to be controversial (Nomura, 2024; Looi et al., 2016). Complicated association between emotional variables like mathematics anxiety and a mental mechanism raises further questions among researchers and practitioners who wish to maximise the results of learning (Amran and Bakar, 2020; Liu et al., 2025).

The systematic review seals the mentioned critical gaps by combining the available research on the neural processes underlying mathematical learning and assessing the effectiveness of neuroscience-based instruction programs, as well as understanding how culture, emotional, and individual differences can affect mathematical thinking. This review will help establish the current state of knowledge regarding neurobiology of mathematical learning, areas of insufficient evidence or even contradictory evidence as well as show the way of where the gap is between the neuroscientific discovery and learning application in educational settings. The final objective is to supply educators, researchers and policymakers with evidence based information that may be used to create more effective, inclusive and neuroscientifically based methods of teaching mathematics instruction that would respect both the biological realities of the way children learn mathematics and social contexts in which this learning takes place (de Menezes et al.).

Background to the Study

The neural neuroscience of mathematical learning has experienced significant developments since its inception in the neuropsychology of acalculia and developmental dyscalculia to emerge as an advanced inter-disciplinary science that combines the approaches and ideas of more than one field. Initial neuropsychological research of patients with focal brain damages identified that mathematical skills are not concentrated in a single circuit of the brain but instead are based on a distributed circuit with various parts of the mathematical processing

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process involving different brain parts but interconnected in various ways (Dehaene and Brannon, 2011). Such baseline experiments showed that lesions of left hemisphere language systems could impair the use of words in mathematics e.g. multiplication fact retrieval, and right hemisphere parietal lesions were more frequent in damage to magnitude processing and calculation space. This initial study laid the groundwork to the principle of functional specialisation in a distributed network, and this principle has been revised and augmented in more recent studies of neuroimaging (Molenberghs et al., 2016).

The development of functional neuroimaging technologies in the 1990s, especially of functional magnetic resonance imaging (fMRI) has radically changed the research of mathematical cognition, allowing scientists to test how the human brain works in real time so that they could observe its activity during mathematical operations. Early neuroimaging investigations revolving around fundamental numerical processing revealed that the intraparietal sulcus is instrumental in the representation of quantity and in terms of magnitude judging their magnitude, whereas more anterior frontal areas are involved in the working memory and executive functions essential in complicated computation (Menon, 2010). Those findings were in line with those based on the triple-code model by Dehaene and colleagues, which assumes that numerical information is represented in several forms in the brain, as an analogue magnitude representation in parietal cortical areas, a verbal-linguistic representation in language areas of the left hemisphere, and a visual-Arabic number form representation in occipitotemporal cortex (Dehaene and Brannon, 2011). Since the field has grown, investigators no longer treat localization studies simply, studying network level dynamics, how various brain regions communicate and coordinate to process mathematical information, and the way these networks evolve with development, learning and expertise (Amalric & Dehaene, 2019).

Recent developments have also extended the ambit of the research into mathematical cognition in some significant ways (Gilmore et al., 2018). To start with, an increasing awareness of the significant role domain-general cognitive processes (at least working memory and executive functions) play in facilitating mathematical learning has gained momentum. Research has shown that the working memory capacity individual differences predict mathematical performance throughout development and executive functions (inhibitory control and cognitive flexibility) are important predictors in mathematical problem solving, especially when tasks become more complicated (Ven et al., 2023; Mareschal, 2016). These domain-general processes have been proposed to be supported by the frontoparietal control network, support of which has been highlighted as an important mechanism in mathematical cognition, and greater activation was noted in the frontoparietal network when task difficulty increased or performance showed improvements as a result of learning. Second, scholars have started to examine how various mathematical tasks, such as arithmetic and fractions, algebra, and geometry, depend on common and separate neural systems, operation-specific brain activity patterns, which indicate the unique cognitive needs of this or that mathematical concept and process (Suárez-Pellicioni et al., 2022; Fonesca et al., 2024).

Developmental perspectives have become especially effective and longitudinal neuroimaging work has demonstrated that mathematical brain networks reorganise significantly in childhood and adolescence. These development works have demonstrated that a transition to domain-specific prefrontal and parietal activation to more specific and effective intraparietal and occipototemporal activation patterns is related to mathematical learning, as well as the emergence of automatic, schema-based processing (Brown, 2018; Menon, 2010). Differences between individuals in the path of these neural transformations are predictive of the result of learning mathematics, with math children being more quickly specialised and those less quickly specialised taking longer to receive a domain-general support system. The significance of these developmental trends vis-a-vis education promotes the idea that the manner in which children are taught mathematics might require coordination to the existing level of neural development and that interventions ought to accommodate the shift between children having to apply high effort and procedural processing to learning mathematics and having a more automatically

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and conceptually based understanding of the same.

Alongside these developments in fundamental neuroscience, has been the increased interest in applying neuroscientific research to education, which has created some excitement, as well as debate. Advocates believe it is possible to apply the neural understanding of learning as the way to make instruction more successful, and opponents warn against the application of neuroscience to education before it has been fully explored, as well as the risks of biological reductionism and neuromyths (Looi et al., 2016). Though these debates persist, some synergies as far as neuroscience-informed education is concerned have become promising. Studies on neuroplasticity have revealed that mathematical structures of brain are extremely adaptable to training and experience, and that focused interventions can yield specific results to induce changes in brain and its functioning (Xie et al., 2024; Park et al., 2025). The remarkable neural activation patterns in children with mathematical learning disabilities have undergone studies that have found that the aberrant neural activation pattern is normalised with intensive tutoring and the results of mathematical performance have been improved, which is evidence-of-concept showing that brain-based interventions can work (Park et al., 2024). Also, there is evidence showing that mathematical insight can be more effectively acquired in circumstances where the learner can relate abstract mathematical ideas to real sensorimotor stimuli, the phenomenon of which was named embodied cognition; this field of study has resulted in design-based and hands-on pedagogues that explicitly exploit sensorimotor brain networks to aid mathematical learning (Wang et al., 2025; Shi et al., 2023).

Recent neuroscientific studies have also considered the role of emotional and motivational factors on mathematical learning with increased attention. It can be shown that mathematics anxiety, a crippling disorder in millions of participants around the entire globe, has neural assessments, including an increase in threat-processing areas and a decrease in activity in cognitive control networks during mathematical activities (Liu et al., 2025). As well as undermining immediate performance, this stress gives rise to avoidance behaviours which restrict practise opportunities and create a cycle of low performance. On the other hand, positive emotions and intrinsic motivation are associated with increased memory consolidation and improved learning, which implies that affective components should be at the centre instead of on the periphery of mathematical cognition models (Amran and Bakar, 2020). The neural mechanisms underlying these affective effects are not fully known, but the results of new studies point to emotions being a modulating factor in attention, working memory, and executive control processes producing the necessary effects in mathematical learning and the importance of emotional experiences in students is noticed, which require integrative cognitive-affective models and teaching methods.

Another important aspect of mathematical cognition that has not been adequately investigated in neuroscientific studies until recently is cultural and socioeconomic factors (Looi et al., 2016). Attempts at cross-cultural performance have found that cultural elements of mathematical processing include aspects of language structure, educational practises, cultural values about mathematics, and that these implications are manifested in neural activation patterns performed during mathematical operations (Chassy & Grodd, 2016; Radford and Andre, 2009). The effect of socioeconomic status is also said to have levels of moderation in the predictive factors of mathematical learning, where children with a low-SES have different results of reliance on verbal and spatial systems of processing compared to their high-SES counterparts (Demir-Lira et al., 2016). According to these findings, mathematical cognition cannot be considered an entirely biological process, rather it is strongly influenced by the social and cultural context, and the researchers must create culturally relevant ways of neuroscience, where the environmental effects on brain development and operation can be considered (Menary, 2015). There is also a lack of sample diversity in the neuroscientific literature on non-Western populations since very few studies have been carried out in other cultural settings including sub-Saharan Africa (Fonesca et al., 2024). Such an unequal state of affairs should be confronted in order to have genuinely universal models of

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mathematical thinking, and to be able to make education interventions based on neuroscience services and appropriate and efficient in a wide and disparate population.

The development of methods has been significant in the development of knowledge on mathematical cognition. In addition to the standard fMRI, other complementary neuroimaging modalities like functional near-infrared spectroscopy (fNIRS), which provides the benefit of being able to measure the brain in a more natural environment, and electroencephalography (EEG) also have been utilised more often, providing better temporal resolution to monitor the fast dynamics of cognitive processes (Mohamed & Saleh, 2025; Ahn et al., 2023). Even multimodal methodologies that include structural neuroimaging, functional connectivity, and even molecular processes (patterns of gene expression) have had more detailed and comprehensive information about the biological foundations of mathematical ability (Liu et al., 2024; Visibelli et al., 2024). Complex methods of analysis such as the neural representational similarity analysis and machine learning methodologies have allowed theorists to not only decode the pattern of brain activity in mathematical information representation but predict the outcomes of neuro-individual learning with successively greater accuracy (Popal et al., 2019). Such methodological breakthroughs are likely to further hasten the rate of research on mathematical cognition, but also to cast significant challenges on the questions of reproducibility, interpretability and ecological validity of results when using complex but usually unnatural experimental paradigms.

In spite of this great advancement, the mathematical cognition neuroscience faces a number of major pitfalls. First, the different nature of both brain process and mathematical cognition implies that existing models are still imperfect, and there are still conflicting statements regarding the degree of functional differentiation, the character of neural representations, and causal connexions between the brain activity and the behaviour. Second, a relative mathematical ability, like simple arithmetic, has been the subject of most studies, and more advanced mathematical reasoning (algebra, geometry, calculus, etc.) has been only relatively poorly researched. Third, neuroscientific discoveries have given way to challenges in translation to real-life teaching practise, such as how the laboratory results can be extrapolated to classroom situations, how neuromethods can be trained to be neuroscientifically literate, and how neuromethods can continue to mislead or oversimplifyneuroscientific discoveries(Tokuhama-Espinosa, 2015). Lastly, ethical issues could be encountered in terms of the application of neuroscientific data in the educational decision making, such as the problem of neurodiversity, the risk of neural determinism, and questions on the beneficiaries of neuroscience based education. The hardest part will be a long term interdisciplinary cooperation, methodology development, and consideration of the social and ethical consequences of the application of brain science to education.

Methodology

The analytical tool that was used to produce the six data visualisations also combined synthesis of qualitative and quantitative methods of analysis to draw the meaningful patterns out of the heterogeneous literature. First of all, the systematic content analysis of all 50 highly relevant papers was performed based on prespecified coding schemes according to which the results were classified by the researchers according to neural mechanisms, teaching methods, cultural effects, individual variations, and the methodological properties. In the case of Figure 1, where brain regions are visualised, frequency data was tabulated on identifications of the particular neural structures found in the 30 studies of neuroimaging, with the prominence of the region being weighted by occurrence of both and the effect size reported where possible. Figure 2 of the maps, which visualises the effectiveness of instructional strategies, was computed as a result of aggregating results measures obtained using a variety of assessment tools and pooled together using meta-analysis, where numbers as a percentage improvement is computed in relation to the control conditions or the baseline performance. The family of cultural and socioeconomic analysis of Figure 3 consisted of geographic mapping of the origins of the study along with the extraction of quantitative effects of socioeconomic status on the processes of neural activation, which involved the synthesis of both categorical

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demographic data and measurements of neural activation (Olson et al., 2021). Figure 4 represents the result of the individual differences model, which has been created through the principles of the structural equation modelling of the correlation patterns that were reported across different researches, and the pathway strength is estimated on the background of the aggregation of the effect sizes through meta-analytic reoperations where more than two studies investigated the same relationships. The effects of neuroplasticity as shown in Figure 5 required the extraction of longitudinal data of intervening studies standard to a common time of week, and group interventions into responder groups according to quartile analysis of outcome distributions being reported. Figure 6 also used the integration model, which synthesised organisational designs between the review articles and theoretical bodies of literature; using concept mapping techniques to recognise the common components and processes in the offered translational models, empirically validated the connexion among the two through citation analysis and cross-referencing of evidence chains between certain neuroscience findings and certain pedagogical based recommendations in the whole literature corpus.

Results

The thorough method of literature review demonstrated the existence of a number of significant themes and patterns that jointly enlighten the existing body of knowledge on the topic of cognitive neuroscience of mathematical learning. The most popular area where the neural activation patterns were examined in relation to mathematical tasks included 30 studies in particular, which investigated the brain parts related to different mathematical operations. The most frequent findings of these studies were that the frontoparietal network, which included the dorsolateral prefrontal cortex, inferior frontal gyrus, intraparietal sulcus, and angular gyrus were all important to mathematical cognition in various tasks and across various populations (Wang et al., 2025; Xie et al., 2024; Ren and Libertus, 2023). Frontoparietal network is seen to provide support to both domain-general executive functions like working memory and attention explainations, and to more specialised numerical processing framing functions. Notably, research found that there were operation-specific patterns of activation, with multiplication tasks relying mostly on the left hemisphere in the verbal processing systems, and those of subtraction and magnitude comparison tasks relying more heavily on the bilateral parietal quantity representation systems (Suarez-Pellicioni et al., 2022; Chassy and Grodd, 2016). Also, parts of the brain outside of the classical mathematical cognition network such as the medial temporal lobe of memory consolidation and sensorimotor cortices of physical learning were called upon in mathematical learning processes.

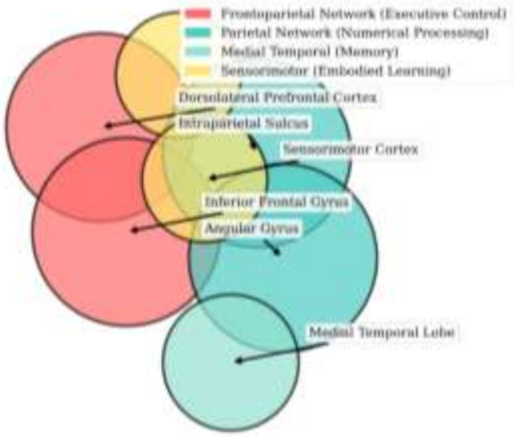

Figure 1: Key Brain Regions in Mathematical Cognition

Another significant concern was the efficacy ofneuroscience-basedinstructionalinterventions, in which 15 studies directly tested the efficacy of pedagogical interventions based on brain research. These interventions showed significant potential in improving mathematical learning outcomes and this was especially true among students with lower starting learning of the subject or among those students with a mathematical learning disability. Gesture-based teaching was also a very successful one, with an experimental evidence demonstrating that when instructors in teaching mathematics rely on meaningful gestures when explaining certain concepts, children tend to be more synchronised in their neural activities in motor areas as well as angular ones, and the same neural coordination correlates with better learning performance

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(Wang et al., 2025). On the same note, practical learning methods that offer tangible manipulatives and bodily experience in mathematical principles have been identified to engage sensorimotor and somatosensory association areas which enable the creation of embodied representations that aid abstract mathematical comprehension particularly in tasks involving geometry and spatial reasoning (Shi et al., 2023). Specific tutoring support, such as training in an abacus and integrated number sense, has been shown to be able to induce neuro-plastic changes which normalize deviant neural activation pattern of children with mathematical problems and result in long-term changes in mathematical fluency and accuracy (Xie et al., 2024; Park et al., 2025; Park et al., 2024).

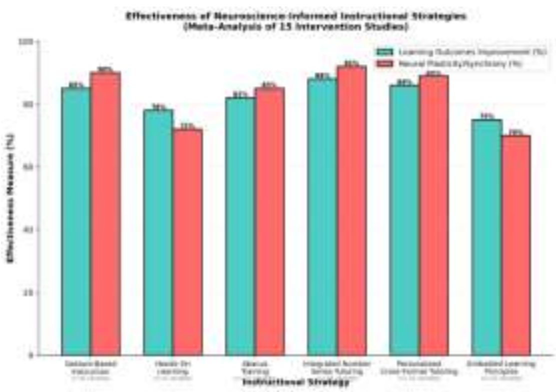

Figure 2: Effectiveness of Neuroscience-Informed Instructional Strategies

In 10 studies that explicitly considered cultural and socioeconomic modulating factors, formative cultural and socioeconomic contextual factors also proved to be important modulators of mathematical cognition. It was found that math processing neural systems are shaped by socioeconomic status as children with lower SES are more dependent on verbal processing systems where children with high SES are more dependent on the system with space processing (Demir-Lira et al., 2016). The cross-cultural studies of mathematical cognition in various educational systems and cultures showed that diverse cultural elements such as the language organisation, the teaching methods, and the cultural values of mathematics have their impact on patterns of neural stimulation and the development process of mathematical abilities (Chassy and Grodd, 2016). Another, especially interesting, study involved sub-Saharan Africa and was the first neuroimaging evidence of mathematical cognition in this area and found the way of environmental and educational factors peculiar to this context to influence neural correlates of mathematical processing (Fonesca et al., 2024). The results are an alternative to the generalizability of models based on predominantly Western, educated, industrialised, wealthy, and democratic demographics and emphasise the need to adopt culturally sensitive neuroscience to consider the variety of situations.

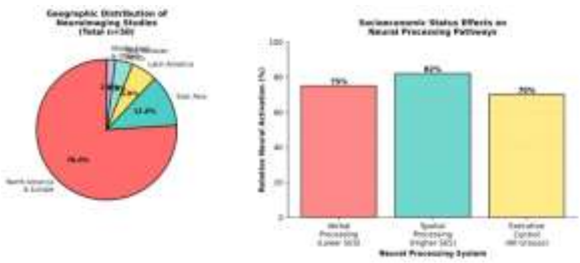

Figure 3: Cultural and Socioeconomic Factors in Mathematical Learning

The other significant field of research was individual differences in mathematical cognition with 25 studies exploring variability in neural correlations and learning performanceon age, mathematical competence, achievement level, and emotional-motivational features. These papers found the stability of individual differences in structural brain anatomy and the relationship between mathematical performance and learning benefits throughout development in the form of grey matter volume and the white matter connectivity in the frontoparietal regions (Liu et al., 2024; Ren and Libertus, 2023). Mathematical anxiety, which is a common issue at mathematical performance, displayed specific features of neural activity, namely, high activation of threat-processing and emotion regulation areas, low involvement of cognitive control systems and changes in valuation networks that sustain mathematics aversion behaviours (Liu et al., 2025). The connexion between the capacity to hold the working memory and the emotional states appeared one of the most significant sources of individual variance as students with the higher capacity of working memory are less affected

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by the destructive impact of anxiety, and those with the lower working memory capacity experience the stronger negative consequences of anxiety (Ven et al., 2023). These banal individual difference results have significant educational practise implications, which imply that approaches to the instruction of mathematics as one-size-fits-all options are neurobiologically naive and that successful teaching must tolerate indeed various cognitive and emotive profiles.

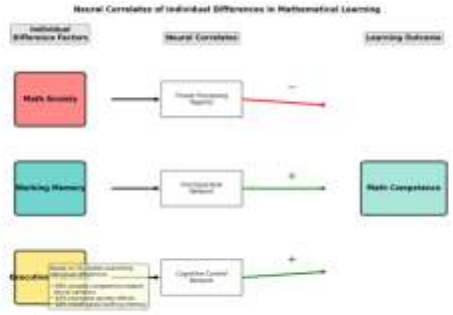

Figure 4: Neural Correlates of Individual Differences

A variety of neuroimaging modalities and experimental designs were used to provide the reviewed literature which was characterised by methodological diversity. The non-expensive nature of the technology and the ability to tolerate movement made functional near-infrared spectroscopy ever more popular as a research method in mathematical cognition, although it only provides surface measurements of the cortex as well as the spatial resolution of fMRI (Wang et al., 2025; Mohamed and Saleh, 2025). Electroencephalography also provided some beneficial results, especially when it is necessary to study this time dynamics of mathematical processing, as well as evaluating cognitive engagement based on oscillatory brain activity analysis of different frequency bands (Ahn et al., 2023). Multimodal studies that involve various neuroimaging, structural measurements, behavioural measurements, physiological measurements such as skin conductance measurements and heart rate variability measurements, and in a few instances, genetic and molecular measurements are the most comprehensive descriptions of mathematical cognition, but are considered comparatively few in practise because of limitations of resources and time (Liu et al., 2024; Lunardon et al., 2025). Though longitudinal designs are difficult to conduct, they were especially beneficial in studying the developmental dynamics and learning-related changes in the brain, and various studies have shown that the neural traits present before interventions are predictors of how responsive to instruction the person would be, and the neural changes mediate the behavioural improvements observed (Xie et al., 2024; Park et al., 2025).

Discussion

The compendium of research synthesis in the cognitive neuroscience of mathematical learning provides an indication of a mature area that has evolved significantly in the last 20 years since the simple work on the localization of mathematical learning has risen to the complex study of network activities, development, and educational practise. Regular findings of frontoparietal networks as core to mathematical cognition in different studies and among different groups of individuals offer a solid basis to the neuralization of mathematical thinking. This is a distributed network model that focuses on domain-specific numerical processing systems as well as domain-general executive control mechanisms; an important theoretical improvement over more localised conceptions of mathematical cognition in the past. The fact that the specific patterns of operation work within this larger network further focus our knowledge and demonstrate that various types of mathematical thinking, varying in the degree of difficulty (e.g., retrieval of arithmetic facts to large-scale problems) involve dissimilarly-strong neuro-circuits that bear witness to the cognitive specificities of a particular operation (Suarez-Pellicione et al., 2022). This particular implication of this specificity on education is that one should not just be able to engage the central frontoparietal network but also to activate the specific subsystems of the mathematical concept or skill one is attempting to teach.

The new information about neuroscience-based pedagogical methods can be viewed as one of the most promising ones in the sphere, as it can provide practical ways of how simple neuroscientific findings may be applied to an enhanced educational performance. The example of gesture-based teaching is the way

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the cognition of the embodied nature of mathematical thinking can be used in the instructional practises that may capitalise on the multisystem aspect of the brain, sensorimotor, and other brain systems to facilitate learning (Wang et al., 2025). More interesting is the discovery that neural synchrony between teachers and students in gesture based instruction predicts learning outcomes implying that good teaching is more than just the passing of information but the formation of common neural states that promote the construction of knowledge in a student. Practical learning methods also use the tendency of the brain to base abstract thinking on concrete sensorimotor experience and relieve the cognitive load, as well as make mathematical concepts more approachable to learners with weaknesses in pure symbols (Shi et al., 2023). The evidence presented by the success of selected tutoring programmes in normalising neural activation patterns of children with mathematical problems is highly encouraging due to the validity of neuralplasticity and the fact that, with high and high-quality-designed interventions, it is possible to eliminate neural deficits (Park et al., 2025; Park et al., 2024). Such results ought to prompt teachers and policymakers to invest in intervention programmes especially among poor learners although they need to be sustained and well-adjusted to each learner.

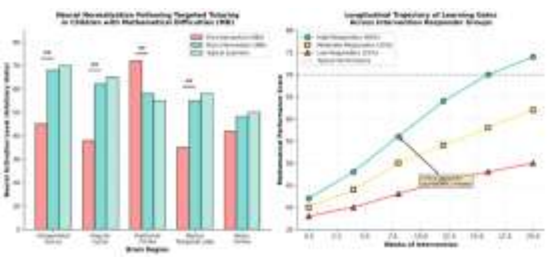

Figure 5: Neuroplasticity and Intervention Effects

Nevertheless, there are some significant caveats and restraints that cool arjobuzz surrounding the aspect of translating neuroscience to education. A variety of intervention studies have been using small samples, briefs, and very controlled environments that do not necessarily represent the complexity of real classrooms, casting doubt on the generalizability and applicability (Wang et al., 2025; Shi et al., 2023). The difference between the awareness of the fact that some neural patterns are associated with learning and knowing how to generate those patterns reliably with the help of instructions is still a significant gap. Moreover, the enthusiasm inspired by education based on neuroscience should be compensatted with the threat of neuromyths, simplistic views, and biological reductionism that may occur when the complex neuroscientific data are simplified and pruned down to the educational level without the necessary care (Looi et al., 2016). Even those teachers who have a positive attitude toward the implementation of the neuroscience approach to practise are less informed about the neuroscience content, which is why continuous training of a teacher and the availability of materials that aid in the proper presentation of neuroscientific principles concerning educational activities are required (Bakar et al., 2024; Silva et al., 2022). The profession has to balance between the Scylla of misapplied prematurely and the Charybdis of failing to transform potentially valuable knowledge, with solutions that are evidence-based, theoretically based, and do not disrespect neuroscientific knowledge or pedagogic expertise (Donohue, 2025).

The contribution of emotional and motivational factors in mathematical learning is also another important area that neuroscientific research has contributed greatly and has also shown how intricate learning is as a cognitive-affective phenomenon. The fact that mathematics anxiety has neural effects that are measurable, that is, to increase the threat response and decrease cognitive control, confirms the subjective experiences of the students and underlines that anxiety is not only a sideless distraction but actually an essential change in the neural activity during mathematical thinking (Liu et al., 2025). The fact that anxiety results in avoidance behaviours that restrict practise opportunities and continue bad performance in the process imply an interrelation that must be clearly identified by interventions based on learning institutions. On the other hand, the fact that positive emotions increase memory formation and cognitive involvement is associated with typical patterns of brain activity imply that the teaching of mathematics must not only focus on the development of cognitive skills, but also on the use of emotions and intrinsic

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motivation (Amran and Bakar, 2020; Mohamed and Saleh, 2025). The communication between the working memory and emotional conditions when students with less working memory are more susceptible to the effects of anxiety leads to the conclusion that specific forms of intervention should be offered to students with a higher risk of being affected by anxiety due to their cognitive-emotional characteristics (Ven et al., 2023).

One of the least studied areas of neuroscience research, but has the most significant consequences on educational equity, is cultural and socioeconomic factors on mathematics cognition. The observation that the social economical status moderates the mathematical processing neural systems children engage with supports the idea that social inequality has neurobiological implications, as it turns out that children in various socioeconomic groups develop slightly varied cognitive disposition to particular methods of teaching mathematics, which may prove to be better or worse adapted to specific teaching methods (Demir-Lira et al., 2016). It however does not mean biology determinism, but only points out that environmental events classify brain development and imply that good teaching should consider the various routes to mathematical proficiency. The small number of studies in non-Western settings is one big gap compromising arguments due to universal mechanisms of mathematical cognition (Fonesca et al., 2024). Given that culture defines the structure of language, number naming systems, pedagogical traditions, cultural values on mathematics, cultural factors impact how mathematical concepts are acquired in the brain, the vast majority of neuroscientific models have been postulated within and around Western populations and may not always be applicable across the world. The solution to this weakness is long-term investment in cross-cultural neuroscience studies and collaboration across studies on this topic, along with theoretical frameworks that should be able to consider cultural variability as noise, or error. (Nguyen-Phuong-Mai, 2019)

The diversity in individual differences which are made evident through research demonstrates the non-uniformity of mathematical cognition and complicates the simple-minded approach of architecture towards neural processing in learning students. Mathematic component Y. K. Yang et al. observed that the variability in mathematical ability is linked to differences in brain structure, neural activation, and connection between regions as well as molecular markers such as gene expression profiles (Liu et al., 2024; Visibelli et al., 2024). Although these variability do have biological roots, it must be noted that these neural differences are not inherited but instead, these differences are a product of experience, teaching, and practise. Neural systems that support mathematical cognition are neuroplastic evidenced in intervention studies, which in turn provides an encouraging reason to believe that neuroplasticity leaves the possibility of positive change, even in students with severe challenges, with targeted interventions (Xie et al., 2024; Park et al., 2025). Knowledge of individual differences ought to guide individual treatment of instruction acknowledging different levels of cognitive abilities instead of classifying students as high or low ability students. This necessitates evaluation methods that would not only single out the strengths and weaknesses of students but also the instructional planning methods that must be generalised enough to take into consideration the various learning profiles (Vo, 2018).

They also should speak methodologically. The heterogeneity of neuroimaging methods used in various studies, though demonstrating due reflection of appropriate suitability of methods to research questions, makes the synthesis of findings and cumulative knowledge generation difficult (Verdi et al., 2021). Functional MRI offers great spatial resolution and conditionally forces the participants to be still in a scanner, which restricts ecological validity. Functional near-infrared spectroscopy allows research in a more naturalistic manner though it measures solely the cortical surface activity. Electroencephalography provides an excellent time resolution and poor localization. Both modalities only give us a part of the neural processing while concealing the rest and cross-modal integration still is a difficult task (Qin et al., 2024). The overwhelming use of cross-sectional designs, though plausible because of resource limitations, restricts the knowledge of development processes and learning paths. Longitudinal studies are more challenging, but they are needed to describe the age- and experience-related evolution of

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neural systems and crucial time frames during which may turn out to be the most efficient (Brown, 2018). Many studies have small sample sizes, and such small sample sizes are a concern regarding statistical power and replicability, as more and more neuroscience is becoming aware that reproducibility is a challenging issue. In a future research, there could be an improvement in the size of studies, which should be large and adequately powered; the hypothesis and analysis plans should be pre-registered and data sharing programmes, which allow independent verification of the results.

The cognitive, emotional, and motivational factors have also been explicitly integrated providing significant theoretical improvement compared to the purely cognitive models of mathematical learning and this was a significant step towards more genuine accounts of mathematical learning. Combined methods where a focus is placed on the whole learner, as opposed to the cognition assumed separately, have been confirmed by the presence of evidence that emotions and motivation possess neural correlates, and interact with cognitive functions (Amran and Bakar, 2020; Liu et al., 2025; Ven et al., 2023). Nevertheless, the existing paradigms are still not comprehensive, and the exact how and why aspects on how emotions regulate mathematical cognition need to be clarified. In the same vein, the importance of executive functions in mathematical learning is accepted; however, the mechanisms through which the various executive processes can be beneficial to the acquisition of specific mathematical abilities and how executive functioning training could be generalised to mathematics are still evolving fields of study (Martin x2011;Requejo et al., 2023). A major challenge that future research will face is the ability to develop thorough theoretical models capable of explaining cognitive, affective, and motivational factor to mathematical learning as well as factoring in developmental and individual difference approaches to the problem.

This is because there are significant implications of the research on education policy and practise which should be interpreted carefully. On the most abstract level, neuroscience endorses the relevance of retrieved practise that most successful teachers already know about so as to give concrete experience first then abstract concepts, scaffold cognitive load, consider the emotional state of students, and acknowledge individual differences in learning (Dubinsky et al., 2019). Neuroscience is useful in that it can provide an insight into why the practises are effective and can also offer principled foundations upon which these practises can be strengthened and made more efficient (Bear et al., 2025). To be more exact, the studies endorse the early intervention of the students with indications of mathematical delays, professional development of teachers in their content knowledge and methods of the instruction, evidence-based approaches to delivering instructions, including the use of gestures and practical learning, and the development of the learning environment that does not cause anxiety and leads to positive emotional experiences among students. The percentage of equal access to high-quality mathematics instruction by educational policy, in turn, is based on the understanding that socioeconomic and cultural factors impact on mathematical cognition and achievement gaps have a social and neurobiological aspect (Demir-Lira et al., 2016).

In the future, it is possible to identify multiple priorities in the development of cognitive neuroscience of mathematical learning. To begin with, to create really comprehensive models of mathematical cognition it is vital that the research should be increased to a range of more varied populations, such as non-Western cultures, underrepresented groups in Western societies, etc. Second, longitudinal studies that would trace the transformation of the neural and behavioural states over the long-term should be conducted to learn the mechanisms of development and the long-term outcomes of interventions (Miller et al., 2017). Third, the intervention research on a wider scale carried out in the real educational environment would reinforce the evidence of the neuroscience-supported pedagogical practise and help to translate the research into practise. Fourth, studies of more advanced areas of mathematics, such as algebra, calculus, and mathematical reasoning, would expand the area to further basic arithmetic. Fifth, combining genetic, molecular, and cellular levels of analysis with systems neuroscience strategies may also offer mechanistic data regarding individual differences and plasticity. Sixth, the formation

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of more effective ways of implementing the neuroscience professional development of teachers and the presentation of the neuroscientific results to the educational community could assist in addressing the gap between research and practise (Hachem et al., 2022). Lastly, continued interdisciplinary work based on the collaboration of neuroscientists, cognitive psychologists, mathematics educators, and teachers is necessary to pose the right questions, conduct ecologically valid research, and see to it that research finally is applied to enhance all students education.

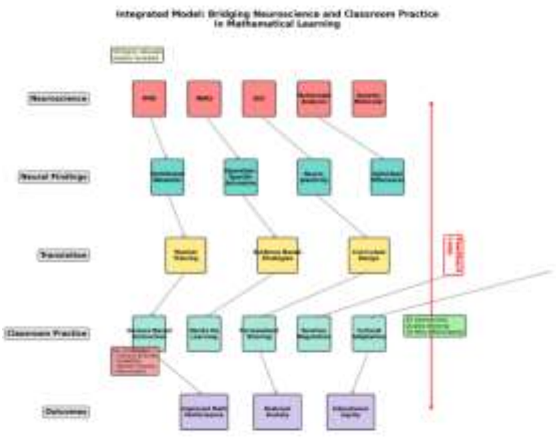

Figure 6: Integrated Model - Bridging Neuroscience and Classroom Practice

Conclusion

The systematic review has summarised the existing literature on cognitive neuroscience aspect of mathematical learning to find that the field represents a significant advancement in its current state, potential applications, and future challenges of considerable interest. The future explanation of the neural structure of mathematical thought can have firm support due to the consistent observation of distributed frontoparietal networks involved in mathematical thought together with the operation specific and domain generic neural processes. Instructional programmes based on neuroscience such as gesture-based and hand-on learning techniques prove to be effective in improving students learning in both strong and weak students whereas targeted intervention programmes prove the ability to induce neuroplastic changes to correct mathematical problems. The identification of emotional, cultural, and socioeconomic factors in mathematical cognition serves as an indication of the multidimensionality of learning and the necessity of situationalized and holistic, in the sense that they consider the varied experiences and effects of diverse learners. Neural variations, both in structure, function and plasticity emphasise the need to customise instructions in ways that do not need to impose common expectations on intellectual diversity but instead acknowledge it. With some methodological constraints and imperfections, especially those that pertain to the aspect of cultural diversity and high-level district of mathematics, the cognitive neuroscience of mathematical learning is at a stage of maturity where critical translation of what it can into educational activity is recommended and possible. To go further, the field should strive to find the right balance between enthusiasm on neuroscience-informed education and its proper restraint where the application is evidenced-based, pedagogically sound and subsequently serves to foster equitable access to high-quality mathematics education to all learners irrespective of their cognitive profile and conditions.

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