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Implications of the Triple Code Model in Mathematics Education

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ABSTRACT

Mathematics education has vital role in enhancing logical reasoning, quantitative thinking, and problem-solving skills in order to make daily life easier and pave the way for further scientific discoveries. However, despite all its significance, many students continue to face problems when it comes to comprehending mathematical notions. Conventional approaches to education are based on repeated practice which is unlikely to take into consideration the neurological aspects of math learning. The recent paper focused neurocognitive theory of Triple Code Model (TCM) for numerical cognition, proposed by Stanislas Dehaene (1992). As per neurocognitive theory of TCM, there are three representational systems used in processing numbers: auditory-verbal code, visual Arabic code, and analog magnitude code. Further, the paper examines how integration among symbolic and non-symbolic representations contributes to arithmetic development and mathematical understanding. The study also highlights the role of paired-associate learning, neurocognitive remediation, and multi-representational instruction in fostering mathematics learning. The paper concludes that mathematics instruction should move beyond rote procedural practice toward cognitively informed and neuroscience-based pedagogical approaches.

Keywords: Triple Code Model (TCM), mathematical cognition, mathematics education, numerical cognition, arithmetic learning

INTRODUCTION

Education is an essential part of life and social development (Callaman & Tagaytay, 2025). Mathematics Education is the cornerstone of education, equips with the necessary cognitive tools to deal with complex problems encountered in daily work and life. Among all disciplines, mathematics education helps us to take day to day decisions in life, equipping individuals with foundational numeracy and abstract problem – solving. Basic knowledge of mathematics and comprehension for living in today's world to deal with everyday activities, primarily such as managing money, measuring time and distance, and counting objects. Therefore, mathematical competence is necessary for participation during the teaching and learning process (NCTM, 2000).

Consequently, exploring the cognitive foundations of numerical understanding has become a significant area of research, leading to the emergence in the area of numerical cognition. Numerical cognition is core pillar of human intelligence that drives everything from basic ground decisions to advanced scientific innovation. It is a field of cognitive neuroscience that study how the human brain perceives and represents numbers & mathematical concepts is known as numerical cognition (Dehaene, 1997; Butterworth, 1999). Generally, students experience difficulties in learning mathematics despite its significance. Traditional teaching practice is often reduced to repetitive procedural practice and memorisation in classrooms,which may not adequately address the underlying cognitive processes responsible for mathematical understanding (Rittle-Johnson & Schneider, 2015). Students may fail to understand mathematical concepts not because of a lack of practice alone, but due to difficulties in processing numerical representations and connecting symbolic and non-symbolic information.

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For years, cognitive scientists have tried to understand how the human brain interprets abstract numerical concepts into meaningful mental representations. Stanislas Dehaene proposed the Triple Code Model (TCM) in 1992, modified in 1995 then in 1997, which revolutionised the field by providing a comprehensive anatomical and functional framework for mathematical processing (Dehaene, 1992; Dehaene & Cohen, 1995; Dehaene, 1997). It has served as a foundational framework for numerical cognition. Numerical cognition helps humans to acquire numerical knowledge. This provides a theoretical explanation of how individuals comprehend and process numerical information effectively. It also suggests the human brain processes numbers in three specific codes: Arabic digits, number words, and analog non - symbolic magnitude representations. Each relies on separate, specialised neural networks in the brain (Skagenholt et al., 2018). The association between three codes is important for arithmetic development (Malone et al., 2019).

The Triple Code Model (TCM) has contributed significantly to understanding arithmetic development, number processing, and mathematical learning difficulties (Dehaene & Cohen, 1995; Dehaene, 1997; Malone et al., 2019). It gives important information about classroom teaching, remedial programs and cognitive intervention approaches through the combination of neuroscience and mathematics. Thus, this paper tries to review the theoretical aspects of the Triple Code Model (TCM) and its implications on mathematics education and numerical learning. The TCM model provides a neuro-cognitive model for the representation of mathematical cognition and numerical learning. The TCM model explains that mathematical processing requires the interaction between auditory-verbal, visual-Arabic and analog-magnitude representations. These interacting systems play different roles in the acquisition of arithmetic skills, estimation, symbolic manipulations, and conceptualization.

The model offers valuable insights into classroom instruction, remediation strategies, and cognitive interventions by integrating neuroscience with math education. Therefore, this paper explores the theoretical foundations of the Triple Code Model (TCM) and examines its implications for mathematics education and numerical learning. This model provides a comprehensive neurocognitive framework for understanding mathematical cognition and numerical learning. The model explains that mathematical processing involves interaction among auditory-verbal, visual Arabic, and analog magnitude representations. These interconnected systems contribute differently to arithmetic learning, estimation, symbolic manipulation, and conceptual understanding

Mathematical Cognition

Mathematical cognition is a cross-disciplinary science which involves the intersection of psychology, cognitive sciences and mathematics education to investigate how humans learn, understand, represent and use mathematics. Mathematical cognition is defined as the processes underlying the acquisition of knowledge in mathematics, i.e., understanding, representing and manipulating numerical and mathematical information (Gilmore, 2023). Research studies in numerical cognition indicate that the initial non-symbolic representations of magnitude arise during infancy (Kochari & Szymanik, 2025). Before schooling, children have an intuitive notion of magnitude and quantity, called Approximate Number System (ANS). This system helps to estimate quantities, compare magnitudes and understand numbers without any formal symbols and language (Núñez et al., 2024). As children acquire language and symbolic knowledge, non-symbolic magnitude representations become associated with verbal number words and Arabic numerals. This integration forms the basis for formal mathematical learning. Therefore, numerical understanding develops through connections among quantities, symbols, and verbal representations. It provides the semantic foundation for symbolic numerical representations. The ability to associate the numerical symbols with their respective quantities is critical for learning arithmetic operations and mathematical achievement. The foundational understanding of magnitude processing plays a significant role in numerical understanding, and its integration with mathematics education impacts the mathematical learning process.

Relation with Mathematics Education

Procedural practice and memorisation are often focussed in traditional mathematics instruction, neglecting conceptual magnitude understanding and representational integration (Rittle-Johnson & Schneider, 2015; Dehaene, 1997). As a result, some students may memorise procedures without developing actual numerical understanding. Numerical information is processed differently, which is one of the most important implications of the TCM in mathematics education. Effective mathematical learning depends on successful integration among verbal, symbolic & magnitude representations. Association between the number words, Arabic numerals & non – verbal magnitude representation is paired–associate learning(Malone et al., 2019).

This model suggests that impairments in one or more representational systems may develop mathematical learning difficulties. Such as weak verbal retrieval may affect multiplication fact recall, poor symbolic processing may impair written calculations and deficient magnitude understanding may affect estimation and conceptual reasoning (Dehaene & Cohen, 1995; Schneider et al., 2017; Odic & Starr, 2018; Jung et al., 2022). Hence, cognitive representations involved in mathematical learning should be addressed beyond repetitive practice as remediation.

Theoretical Framework

One of the most influential neurocognitive models, proposed by Stanislas Stall (1992), explains how the brain processes numerical information through three distinct interconnected neurocognitive modules, each localised to specific neural structures, which are further classified as: Symbolic (visual and verbal) and non–symbolic (magnitude representation).

Numerical information is further processed through three different interconnected representational systems, each contributing uniquely to mathematical learning.

1. **The Auditory – Verbal Code (Word – frame):** This code processes numbers as verbal and linguistic representations, heavily dependent on verbal working memory and rote phonological loop retrieval. It is localised in the left perisylvian, part of brain (Dehaene et al., 2003, 2005) & angular gyrus area (Grabner et al., 2009). It is associated with rote memorisation, verbal counting, and arithmetic fact retrieval (Grabner et al., 2009). Mathematical tasks such as recall of multiplication tables and verbal counting depend strongly on this code. This code contributes significantly to counting, verbal arithmetic (Ünal et al., 2023; Duricy, 2023)), fact retrieval, and mathematical language processing (Sokolowski et al., 2023; Fritz et al., 2025). Students with weaknesses in verbal memory may experience difficulty recalling arithmetic facts despite repeated practice.

2. **The Visual Arabic Code:** It views and manipulates numbers as spatial configurations of alphanumeric symbols, governs the syntax of written equations & column alignment, localised in the ventral occipitotemporal areas (including number form areas). It allows people to be able to recognize the symbol, manipulation of written calculations and spatial structure in math. This coding system is important when there is a need to read numerical symbols, written calculations, columnar alignment, algebraic manipulations, symbolic mathematical operations. Problems associated with this coding system can cause symbol recognition problems, place value problems, written arithmetic (Dehaene et al., 2003; Skagenholt et al., 2018; Vogel et al., 2015).

3. **The Analog Magnitude Code:**

This coding system is responsible for the semantic processing of quantities, estimation and proportion. In this system the numbers are coded as quantities on the mental number line that lies bilaterally in the intraparietal sulcus (IPS). This code is responsible for processing the core semantic understanding of quantity, estimation, and proportion. It represents numbers as continuous quantities along a spatial mental number line and is primarily localised in the brain part bilaterally in the intraparietal sulcus (IPS). This representational system enables individuals to estimate quantities, compare numerical magnitudes, reason proportionally, and understand numerical relationships without relying on verbal or symbolic representations. This code is essential in the development of number sense, estimation skills, quantity comparison, fraction understanding, and proportional reasoning. By supporting the intuitive comprehension of numerical magnitude, it forms the conceptual foundation for higher-order mathematical thinking. Consequently, weaknesses in magnitude representation may hinder students' conceptual understanding of mathematics, leading to difficulties in estimation, numerical comparisons, fraction concepts, and proportional reasoning (Dehaene et al., 2003; Piazza et al., 2004; Vogel & De Smedt, 2021).

In early infancy, rudimentary non – symbolic magnitude representation is present in the cognitive system of child and it is connected with visual and phonological representation that the child has acquire during language acquisition. The understanding of the magnitude provides the basis for the meaning of Arabic digits and number words. Magnitude understanding is coded in the approximate number system. It is very much important for the numerosity estimation and representation (Skagenholt et al., 2018). These systems interact continuously during mathematical processing & contribute differently to arithmetic operations, estimation & numerical processing. Recent researches in the field of neurocognition utitlised various neuroimaging modalities such as functional Magnetic Resonance Imaging (fMRI), Electroencephalogram (EEG) that provided empirical support for the Triple Code Model (TCM) (Rockhill et al., 2024; Skagenholt et al., 2018; Moreel et al., 2026). Neuroimaging studies have demonstrated activation of intraparietal sulcus during magnitude comparison tasks

(Piazza et al., 2004), activation of left language areas, particularly the angular gyrus, brain area, during arithmetic fact retrieval (Grabner et al., 2009), and activation of occipitotemporal regions, brain area during symbolic number recognition (Shum et al., 2013). These findings validate the neurocognitive basis of numerical processing and support the importance of multi-representational mathematical instruction. Studies indicate that different mathematical operations activate distinct neural regions associated with the three representational systems (Dehaene et al., 2003; Delazer et al., 2003; Skagenholt et al., 2018).

Contribution of Triple Code Model (TCM) in Mathematics Education

Implications of Triple Code Model in mathematics education include instruction, learning, assessment, conceptual understanding, teaching strategies and curriculum. The model indicates the importance of the integration of verbal, symbolic and magnitude representations in teaching of mathematics in order to promote a multi-representational approach to learning mathematics. In addition, it highlights the importance of conducting activities on estimating, comparing and quantity reasoning in order to increase number sense and conceptual understanding. This model stresses the importance of using multiple representations including number line, visual representation, language of mathematics and symbols to enable students to make connections among numerical concepts (Dehaene et al., 2003; Vogel & De Smedt, 2021).

Hence, the model encourages flexible thinking and deep understanding as it encourages changing information from one form to another form (verbal, visual and symbolic) (Ainsworth, 2006; Dehaene et al., 2003; Mayer et al., 2025). Furthermore, the model stresses the importance of having a balanced approach in mathematics instruction in which the teaching strategy includes activities to connect numbers with symbolic representations (Rittle-Johnson & Schneider, 2015; Vogel & De Smedt, 2021). Arithmetic skills, problem solving and reasoning are developed through experiences which involve quantity reasoning and symbolic manipulation (National Research Council, 2001; Dehaene, 1997). This means that educational practices should provide possibilities for students to communicate about mathematical ideas, visualize quantities, and make various representations of the relations to improve mathematical communication and conceptualization (NCTM, 2000; Ainsworth, 2006; Australian Association of Mathematics Teachers [AAMT], n.d.). Also, it helps in the process of diagnostic evaluation by enabling the identification of a particular representational system that leads to problems in learning. Thus, recognizing whether problems are caused by deficiencies in verbal, symbolic, or magnitude processing, a teacher can offer the right interventions and focus on the weaknesses of a particular nature instead of just repeating the processes. This will lead to more efficient neurocognitive treatment and better outcomes in mathematics (Whitacre et al., 2020; Siemann & Petermann, 2018). Level which paired-associate learning predicts the development of arithmetic skills remains to be revealed (Malone et al., 2019). Moreover, the TCM serves as a helpful guide in the development of instructional activities that can help create connections between the representations of verbal, symbolic, and magnitude nature. These activities may include estimation, number line, representation translation, and paired-associate learning exercises that will make students go through number words, numerical symbols, and quantities. Moreover, the model presents promising areas of research for the development of interventions grounded in scientific research for math learning disabled students because it focuses on numeracy deficits rather than purely procedural exercises.

Future research should therefore examine the effectiveness of classroom-based TCM-informed interventions across diverse educational contexts and age groups to establish their impact on mathematical achievement and long-term retention of mathematical concepts (Dehaene et al., 2003; National Research Council, 2001; Vogel &

De Smedt, 2021). Although role of representational integration in numerical cognition is highly supported by increasing evidences but still, how instructional interventions based on the Triple Code Model can be systematically implemented in classroom settings is less explored. Moreover, particularly among secondary school student level to which paired-associate learning contributes to the development of arithmetic fluency, conceptual understanding, and mathematical performance remains insufficiently explored (Malone et al., 2019).

Relationship between Paired-Associate Learning in Arithmetic Development

Paired-associate learning (PAL) is the ability to learn and remember relationships between different types of information, such as words, symbols, and quantities. In mathematics, this ability is important as it allows teachers to adapt the teaching style to match the needs of the students to connect number symbols with number words and quantities. For example, a student must understand that the symbol "5," the word "five," and a set of five objects all represent the same numerical idea. These connections form the basis of meaningful numerical understanding. The triple code model assumes that there are three ways of representation of the information: verbal, symbolic and magnitude. Paired-associate learning helps students build links among these systems, making it easier to process and use numerical information. Research has shown that students with stronger paired-associate learning skills tend to perform better in arithmetic fact retrieval, symbolic number processing, and numerical fluency. These skills also support the development of mathematical memory and overall mathematical competence (Malone et al., 2019; Vogel & De Smedt, 2021; Whitehead & Hawes, 2023). From an educational point of view, activities that engage students in connecting numbers, words, and quantities through various representations will enhance these associations. This type of activity may help some students who find mathematics difficult by helping them grasp the relationships between numbers. Thus, including paired-associate learning in teaching mathematics aligns with the ideas behind the Triple Code Model and will help promote better mathematical skills.

It becomes increasingly important to conduct research on the Triple Code Model (TCM) which describes the brain mechanisms of numerical processing and it is essential because children have to associate to the application of the theory in the educational setting. The capacity of the Triple Code Model (TCM) to assist in designing class-based practices has not been studied thoroughly, while this theory has provided valuable insights on the neurocognitive basis of numerical cognition. Therefore, the development of class-based interventions, teaching strategies & educational practices which will allow teachers to address the individual learning needs of their students is needed. Interventions, which specifically focus on representational deficits associated with magnitude understanding, symbolic processing, and arithmetic fact retrieval, contribute to more effective mathematical learning. Hence, moving the Triple Code Model from the neurocognitive framework to the pedagogical framework can be seen as one of the best options for mathematics education research.

Further studies on the Triple Code Model should not be limited to the model as a framework in neurocognitive explanation of the process of numerical cognition but rather extend the model's use to real-world educational contexts. In this regard, future researchers can consider the integration of TCM with self-regulated learning, metacognition, mathematical resilience, mathematics anxiety, and problem-solving strategies in order to better understand the process of mathematical learning. Integration of these constructs will enable researchers to have an understanding of the interaction between cognitive, motivational, and emotional factors along with verbal, symbolic, and magnitude representation during mathematical activities. The use of the Triple Code Model together with some other theories like Dual Coding Theory, Cognitive Load Theory, and multiple-representation theories is expected to offer insightful information in designing learning interventions in terms of conceptual understanding, procedural fluency, and number sense. Further studies may consider the effectiveness of technology-enhanced learning environments based on TCM.

By bridging cognitive neuroscience and educational practice, the Triple Code Model has the potential to inform evidence-based teaching strategies that strengthen mathematical reasoning, communication, achievement, and long-term engagement with mathematics (Dehaene, 1997; Dehaene et al., 2003; National Research Council, 2001; Ainsworth, 2006; Vogel & De Smedt, 2021). Understanding how students cognitively process mathematical information while regulating emotions and persistence may contribute to more comprehensive mathematics education models (Pekrun, 2006; Goldin, 2002).

Development of symbolic and non – symbolic representation across different educational stages can be examined by the longitudinal studies which help in identifying critical developmental periods for intervention. To understand how linguistic diversity influence mathematical learning and numerical understanding, role of multilingualism should also be identified as future research direction in numerical cognition, particularly within Indian classrooms where students frequently learn mathematics through multiple languages. Research can further explore the role of paired-associate learning activities in strengthening connections among number words, symbols, and quantities. Classroom-based experimental studies may examine whether such interventions improve arithmetic fluency and conceptual understanding. Beyond exploring the developmental and linguistic factors influencing numerical cognition, future research should investigate instructional practices that facilitate the integration of verbal, symbolic, and magnitude representations, according to the Triple Code Model. Arithmetic fluency and conceptual understanding can be enhanced by strengthening connections among number words, symbols and quantities. This can be further done by exploring the role of paired associate learning activities and conducting classroom – based experimental studies for developing an intervention.

CONCLUSION

The TCM theory has many applications to mathematics instruction as it takes into account the challenges associated with mathematical learning that may result from inadequacies in particular representation systems and not only due to insufficient practice. As a result, teaching of mathematics should involve using verbal explanations, symbolic representations, verbal models and magnitude representations to develop understanding at the conceptual level. Neurocognitive findings can be used in classroom practices through cooperation of mathematicians, neuroscience, and curriculum developers to make teaching of mathematics better and more inclusive.

Through bringing together neurocognitive findings and traditional practices in teaching of mathematics, the Triple Code Model (TCM) provides several valuable guidelines for instructional design and remediation as well as future research in mathematics education. Research can focus on the effectiveness of these strategies in different educational contexts and the incorporation of these strategies with other theories of cognition and pedagogy. In conclusion, the Triple Code Model connects neuroscience with math education theory and provides an excellent basis for improvements in teaching and learning mathematics.

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