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EFFECTS OF STEMEN TEACHING MODELS ON MATHEMATICAL LITERACY AND MATHEMATICAL PROBLEM-SOLVING

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ABSTRACT

Purpose - Mathematical literacy and mathematical problem-solving are crucial abilities that link mathematics content to real life applications, facilitating both mathematics understanding and mathematical processes. The present study aimed to investigate the effectiveness of the STEMEN (STEM and educational neuroscience) teaching model in enhancing mathematical literacy and problem-solving skills.

Methodology - This study adopted a pre-test and post-test control group design. Among 156 Grade 9 students from a secondary school in Phayao, Thailand, 70 were randomly selected. The STEMEN teaching model was implemented in the experimental group, while the 5E teaching model, typically used in a normal classroom was employed in the control group. Two types of tests, namely the mathematical literacy test and the mathematical problem-solving test, were used as research instruments. Pre and post-data were collected from both the experimental and control groups. Repeated measures ANOVA with Wilks' lambda was employed to analyze the mean comparison for mathematical literacy and mathematical problem-solving.

Findings - The findings revealed that the mean scores for mathematical literacy and mathematical problem-solving were relatively higher in the STEMEN teaching model group compared to the 5E teaching model group. These results provide insights into the effectiveness of the STEMEN teaching model in enhancing learning outcomes, particularly mathematical literacy and problem-solving in mathematics.

Significance – The results of this study showed that the STEMEN teaching model was effective in increasing learning outcomes, including mathematical literacy and problem-solving. These outcomes should enable teachers to design effective and efficient instructional strategies for enhancing mathematical literacy and problem-solving in classrooms.

Keywords: STEM education, educational neuroscience, STEMEN teaching model, mathematical literacy, mathematical problem-solving.

INTRODUCTION

In the 21st century, mathematical literacy is an essential life skill, enabling learners to understand mathematical in-depth concepts and apply them to real-world situations outside the classroom. Moreover, it is a crucial ability that should be taught in schools (Bolstad, 2020; Maryani & Widjajanti, 2020; Rizki & Priatna, 2019; Sumirattana et al., 2017). Additionally, mathematical problem-solving is a vital mathematical process that should be emphasized in education because it affects learners' ability to apply their mathematical knowledge and skills to solve real-world problems (Göktaş & Yazıcı, 2020; Li & Disney, 2021; Özcan, & Eren Gümüş, 2019; Piñeiro et al., 2021). Therefore, both mathematical literacy and problem-solving should be continuously promoted in classrooms.

The National Institute of Educational Testing Service, Thailand (2010 as cited in Sumirattana et al., 2017) reported that Thai Grade 9 students scored below 50 percent on average in mathematics on the Ordinary National Educational Test. Moreover, according to the Programme for International Student Assessment (PISA) conducted by the Organisation for Economic Cooperation and Development (OECD), the average scores for mathematical literacy among Thai students were 432, 417, 417, and 419 points in the years 2000, 2003, 2006, and 2009, respectively. These scores were lower than the OECD average for those years (OECD, 2004, 2007, 2010). Furthermore, as reported by the Institute for the Promotion of Teaching Science and Technology (2021), PISA found that Thai students' average mathematics scores in 2012, 2015, and 2018 were 427, 415, and 419 points, respectively, with the 2018 score being below the OECD average. These findings highlight inadequacies in the performance of Thai students and the quality of mathematics instruction. Students often cannot recall or understand the mathematical knowledge they have learned, solve problems, or recognize the importance of such knowledge. They also tend to perceive mathematics as irrelevant and inapplicable to their daily lives (Phetthai & Poonpaiboonpipat, 2020; Sumirattana et al., 2017). Additionally, Thai Grade 9 students lack mathematics problem-solving skills, potentially hindering their ability to solve self-mathematics problems, complex mathematics, and creative mathematics problems (Srikoon, 2021b). After completing their studies, students often cannot apply their mathematics knowledge to solve problems in daily life, lack confidence in using mathematical content, and have misconceptions and errors in mathematical processes (Napaphun, 2018). Therefore, improving mathematical literacy and problem-solving is an urgent issue for Thai students.

There has been a revolution in STEM education in teaching and learning at all educational levels. Specifically, the integration of science, technology, engineering, and mathematics has led to the emergence of new structures and innovations, affecting both the physical environment and classroom activities (Bybee, 2010; Kelly & Knowles, 2016; Penprase, 2020). Consequently, STEM education has created a need to explore the context of science education broadly and deeply, along with the scope of innovations that have reshaped STEM teaching in classrooms. This integrated approach aims to provide more effective methods to enhance students' ability to solve various problems in our dynamic world and society (Corlu et al., 2014; Gül & Taşar, 2020; Kelly & Knowles, 2016; Penprase, 2020).

STEM education is recognized as a global imperative, influencing learning in the 21st century. Educators have endeavored to adopt quality in-service instruction and STEM pedagogy best practices, while also fostering collaboration opportunities for future STEM-related studies (Li et al., 2020; Margot & Kettler, 2019). However, Simoniello and Watson's (2018) SWOT analysis identified three significant shortcomings of STEM education: (1) inadequate support for education, inconsistent school leadership, liability limitations, large class sizes, and religious and political interference degrading science education; (2) challenges in bridging disciplinary disparities; and (3) the recruitment and retention of quality STEM professionals primarily through salary and compensation, alongside insufficient funding for education, a lack of preservice and professional development for STEM, difficulties in assessing student performance in STEM activities, and time constraints. Given these persistent issues, STEM education should be continuously developed to create high quality teaching models (Kelley & Knowles, 2016; Leung, 2020; Martín-Páez et al., 2019; Takeuchi et al., 2020).

In response to these problems, educators have proposed various ideas to improve STEM education management. According to findings of the SWOT analysis by Simoniello and Watson (2018), STEM education should focus on improving existing programs and teachable moments. A critical approach to developing STEM education by Kelley and Knowles (2016) revealed a conceptual framework for integrated STEM education, suggesting that situated cognition theory underpins most STEM content. This theory posits that the application of knowledge and skills is as important as their acquisition (Brown et al., 1989; Lave & Wenger, 1991; Putnam & Borko, 2000). Therefore, educational neuroscience, a modern learning theory grounded in cognitive approaches should be leveraged to enhance STEM education.

Educational neuroscience is an emerging multidisciplinary field that combines fundamental research in neuroscience and psychology with education (Byrnes & Vu, 2015; Kalbfleisch, 2015; Tandon & Singh, 2016; Thomas et al., 2018; Srikoon, 2023). Advancements in educational neuroscience have shown impressive potential effects on educational practices (Brookman, 2016; Jamaludin et al., 2019; Luque-Rojas et al., 2022; van Der Meulen et al., 2015). Specifically, these developments have built a body of knowledge that is consistent with reliable theories, providing abundant scientific evidence about the neuroscience of brain-behavior relationships. This has contributed to the development of new pedagogy, learning, and curriculum strategies (Edelenbosch et al., 2015; Hachem et al., 2022; Jamaludin et al., 2019;

Norwich, 2015). As a result, many instructional researchers have attempted to develop novel teaching models grounded in educational neuroscience for innovative education. For instance, Runganurak et al. (2022) developed a learning activity by combining design-based learning with educational neuroscience. Srikoon (2020) constructed a teaching model integrated with working memory training based on educational neuroscience. Additionally, Srikoon (2021a) combined research-based learning with cognitive training to design new learning activities, and Srikoon and Tippala (2022) integrated the open approach with mental training learning activities. These studies suggest that integrating educational neuroscience with traditional teaching models can effectively improve learning outcomes and provide insights into new learning activities, potentially leading to an evolution of instructional science in the next decade (Bowers, 2016; Goswami, 2016).

STEM education combined with educational neuroscience (STEMEN) is derived from Kelley and Knowles's (2016) conceptual framework for integrated STEM education and various educational neuroscience disciplines. Kelley and Knowles (2016) stated that STEM can be underpinned situated cognitive theory, emphasizing that understanding how to employ knowledge and skills in practice is as crucial as developing them. According to reviews conducted by Goswami (2016), Srikoon (2023), Sweatt (2010), and Tandon and Singh (2016), educational neuroscience combines traditional cognitive theory disciplines, as research on the mind, brain, and behavior has expanded through advancements in medical instruments and neuroscience. Therefore, this study aimed to examine the effectiveness of STEM education based on educational neuroscience in enhancing mathematical literacy and problem-solving skills.

RESEARCH OBJECTIVE

This study aimed to investigate the effectiveness of STEM education-based educational neuroscience (STEMEN) in improving mathematical literacy and problem-solving skills. The study was carried out following the development of the STEM teaching model, which is based on STEM education and an in-depth understanding of modern educational neuroscience. The model was evaluated by three experts before its implementation. Therefore, the objectives of the present study were:

i. To investigate the effectiveness of the STEMEN teaching model in enhancing mathematical literacy scores among Grade 9 students before and after the implementation of the STEM education-based educational neuroscience teaching model (experimental group) and the 5E teaching model (control group).
ii. To investigate the effectiveness of the STEMEN teaching model in enhancing mathematical problem-solving skills between the experimental and control groups.

LITERATURE REVIEW

STEM Education

The scope of STEM education involves the integration of instruction in science, technology, engineering, and mathematics, which can be conceptualized to design contemporary learning activities (Bybee, 2010; Leung, 2020; Sperling et al., 2024). Despite its advantages, educators should seek more effective ways to develop STEM teaching (Kelley & Knowles, 2016; Martín-Páez et al., 2019; Takeuchi, 2020). Kelly and Knowles's conceptual framework for integrated STEM education comprises four main principles of situated STEM learning: engineering design, scientific inquiry, technological literacy, and mathematical thinking. Moreover, according to Kelly and Knowles (2016), STEM education can be based on situated cognitive theory, which posits that the physical and social settings of a learning activity play a crucial role in the learning process. Learning how to use knowledge and skills is as important as acquiring them (Brown et al., 1989; Lave & Wenger, 1991; Putnam & Borko, 2000). The four principles of STEM learning (Chen et al., 2024; Kelly & Knowles, 2016) are explained as follows.

(1) Engineering design enables students to draw on mathematics and scientific inquiry to develop experiences. This process allows them to use their experiences and provides opportunities to develop new scientific and mathematical knowledge through design analysis and scientific investigation.

(2) Scientific inquiry must be relevant to a context, and the ability to apply scientific knowledge to real-world problems can promote a comprehensive understanding of the acquired knowledge. "Minds-on" experiences, which are incorporated in constructivist methods for

science learning, are crucial for scientific inquiry. To prepare teachers to teach through scientific inquiry, they should be provided with enhanced pedagogical knowledge and exposed to real-world scientific investigations and experimentation practices.

(3) Technological literacy includes two standard views of technology: an engineering view and a humanities perspective. The former is described as the instrumental perspective associated with materials, while the latter is based on the human purpose of technology to achieve specific human tasks. The humanities view of technology acknowledges that technology is subjective, thereby presenting opportunities to examine its influences on aspects such as culture, society, the economy, politics, and the environment.

(4) As for mathematical thinking, for students to learn mathematics and recognize the relationship between what they have learned in school and what is required for STEM career skills, it is necessary to adopt STEM activities associated with mathematical analysis for assessing designed solutions.

Educational Neuroscience

Educational neuroscience is a multidisciplinary field that integrates basic research in neuroscience and psychology into education (Byrnes & Vu, 2015; Kalbfleisch, 2015; Tandon & Singh, 2016; Thomas et al., 2018). Advances in educational neuroscience research have laid a foundation for designing learning activities (Brookman-Byrne & Commissar, 2019; Cuevas et al., 2023; Edelenbosch et al., 2015; Jamaludin et al., 2019). Two main approaches in educational neuroscience were utilized to construct a teaching model. First, neuroconstructivism derived from constructivist theory provides insights into how new experiences are constructed for human learning (Karmiloff-Smith, 2009; Westermann et al., 2007). Westermann et al. (2007)'s neuroconstructivism in educational neuroscience comprises five constraints on cognitive development: genes, encellment, embrainment, embodiment, ensocialment, and interaction between constraints. (1) Genes: Probabilistic epigenesis highlights the interactions between experience and gene expression. (2) Encellment: Neural constructivism underscores the experience-driven development of neural structures. (3) Embrainment: The 'interactive specialization' view of brain development emphasizes the interactions between distinct brain areas. (4) Embodiment: Highlights how the body contributes to cognitive development. (5) Ensocialment: A constructivist approach to cognitive development with a focus on proactive knowledge acquisition. (6) Interaction Between Constraints: Focuses on the influence of the social environment on children's development. Additionally, Hardiman (2012) established six goals for a 21st century teaching model based on data in neuroscience and cognitive science. (1) Establishing the emotional climate for learning: Integrates activities into lessons to create an emotional connection to the content, enhancing its significance and relevance for students. (2) Creating the physical learning environment: Encourages teachers to promote movement and provide a sense of order and beauty in classroom management. (3) Designing the learning experience: Shows students how learning goals and objectives relate to routine tasks and contribute to the acquisition of knowledge, skills, and concepts. (4) Teaching for mastery of content, skills, and concepts: Investigates how incorporating visual and performing arts can promote knowledge retention. (5) Teaching for the extension and application of knowledge: Emphasizes creativity and innovation in education, promoting divergent thinking and problem-solving through learning experiences. (6) Evaluating learning: Examines how continuous evaluation, such as portfolios, student-generated works, and performance-based assessments, can improve learning and memory. Unlike traditional learning theory, neuroconstructivism provides a broader and more detailed understanding, offering more information for developing educational innovations.

STEM education combined with Educational Neuroscience

The principles of the STEM education-based educational neuroscience teaching model, referred to as the STEMEN teaching model, are outlined as follows:

(1) Integration of four disciplines: The integration of science, technology, engineering, and mathematics, induces changes in genes, neural activity, brain function, the body, environment, and collaboration among all constraints.

(2) Two dimensions of the teaching model: The STEMEN teaching model comprises two dimensions: syntax and the technological learning environment.

The syntax of the STEMEN teaching model is synthesized based on engineering design, scientific inquiry, and insights from educational neuroscience research.

The congruence analysis of STEM education and educational neuroscience for the STEMEN teaching model involves two dimensions. The first section lays the foundation for developing the syntax of the STEMEN teaching model, as elaborated in Table 1.

Table 1

Synthesizing the Syntax of the STEMEN Teaching Model

Engineering design (Kelly& Knowles, 2016)	Scientific inquiry (Kelly& Knowles, 2016)	Educational neuroscience	STEMEN syntax
(1) Beginning with a problem, need, or desire that leads to an engineered solution.	(1) Beginning with a question about a phenomenon.	(1) Establish an emotional climate (Hardiman, 2012). (2) Stimulate genes, neural activity, and body with the real-world environment (Westermann et al., 2007).	(1) Entertainment: Learners' emotional climate is enhanced and aroused by real-world environment and situation problems.
(2) Using models and simulations to analyze existing solutions.	(2) Using models to develop explanations about natural phenomena.	(3) Designing the learning experience (Hardiman, 2012). (4) Using the embrainment and embodiment principles (Westermann et al., 2007).	(2) Enclosure: Learners form a connection of cognitive models related to problem-solving and analysis.
(3) Engineering investigation to obtain data necessary to identify criteria and constraints and test design ideas.	(3) Scientific investigation using a systematic approach in the field or lab.	(5) Teaching for mastery of content, skills, and concepts (Hardiman, 2012). (6) Using the ensocialment principle (Westermann et al., 2007).	(3) Encounter: Learners perform an investigation through proactive activity and draw on content, skills, and concepts to assess ideas related to the environment and design ideas.
(4) Analyzing and interpreting data collected from tests of designs and investigations to locate optimal design solutions.	(4) Analyzing and interpreting data from scientific investigations using a range of tools for analyzing and locating patterns, e.g., tabulation, graphical interpretation, visualization, and statistical analysis.	(7) Teaching for the extension and application of knowledge or creativity and innovation in education (Hardiman,2012). (8) Using the principle of interactions between constraints (Westermann et al., 2007).	(4) Ensuring: learners draw on knowledge to analyze and assess obtained data and to identify optimal design solutions.

(continued)

Engineering design (Kelly& Knowles, 2016)	Scientific inquiry (Kelly& Knowles, 2016)	Educational neuroscience	STEMEN syntax
(5) Mathematical and computational thinking are integral to design by allowing engineers to run tests and mathematical models to assess the performance of a design solution before prototyping.	(5) Mathematical and computational thinking are fundamental tools for representing variables and their relationships. These ways of thinking allow for making predictions, testing theories, and locating patterns or correlations.	(9) Teaching for the extension and application of knowledge or creativity and innovation in education (Hardiman, 2012). (10) Using the principle of interactions between constraints (Westermann et al., 2007).	(5) Encompassment: learners employ mathematics knowledge for explaining and testing different phenomena and making predictions. Moreover, they identify the correlations between variables to design solutions and prototypes, respectively.
(6) Constructing and designing solutions using a systematic approach to solving engineering problems based on scientific knowledge and models of the material world; designed solutions are optimized by balancing constraints and criteria of existing conditions.	(6) Constructing scientific theory to provide explanations is a goal for scientists and grounds the explanation of a phenomenon with available evidence.	(11) Teaching for the extension and application of knowledge or creativity and innovation in education (Hardiman, 2012). (12) Using the principle of interactions between constraints principle (Westermann et al., 2007).	(6) Enhancement: learners apply their knowledge, solutions, and prototypes to improve, construct, and design solutions based on the environmental context.
(7) Arguments with evidence are crucial to engineering for locating the best possible solution to a problem. The location of the best solution is based on a systematic approach to comparing alternatives, formulating evidence from tests, and revising design solutions.	(7) Arguments with evidence are essential to scientific practices by providing a line of reasoning for explaining a natural phenomenon. Scientists defend explanations, formulate evidence based on data, and examine ideas by engaging in discussions with experts and peers to refine ideas.	(13) Teaching for the extension and application of knowledge or creativity and innovation in education (Hardiman, 2012). (14) Using the principle of interactions between constraints principle (Westermann et al., 2007).	(7) Enlightenment: learners present arguments with empirical evidence for locating the best solution and then revise the proposed solution for the next cycle.

As illustrated in Table 1, both engineering design and scientific inquiry principles do not give attention to genes, neural activity, the brain, or the essence of internal learning processes. Hence, adding those components to the STEMEN teaching model is reasonable. The technological learning environment is shown in Table 2.

Table 2

Synthesizing the Technology Learning Environment of the STEMEN Teaching Model

Engineering perspective of technology (Kelly& Knowles, 2016)	Humanities perspective of technology (Kelly& Knowles, 2016)	Educational neuroscience	STEMEN technology learning environment (DO)
(1) A distinct body of knowledge.	(1) More than a sum of tools, instruments, artifacts, processes, and systems.		
(2) An activity or a way of doing.	(2) Influences the structure of the cultural/social order, regardless of user intentions.	(1) Using the principles of Ensocialment and interaction between constraints (Westermann et al., 2007).	(1) **D**iversity of technology learning environment, both concrete and abstract objects.
(3) Design, engineering, production, and research procedures.	(3) Serving human values and influencing value formation.		(2) **O**pen accessing channel for scaffolding STEMEN procedures.
(4) Physical tools, instruments, and artifacts.	(4) Autonomous social and economic forces that often override traditional and competing values.	(2) Establishing the emotional climate for learning (Hardiman, 2012).	Both principles are used to promote learning by doing.
(5) Organized integrated systems and organizations that are used to create, produce, and use technology.	(5) Capable of unanticipated positive as well as destructive social and economic consequences.		

Mathematical Literacy

Mathematical literacy refers to the capacity of each learner to formulate, identify, understand, implement, employ, and interpret mathematics in various contexts relevant to everyday life (Demir & Altun, 2018; OECD, 2010; Retnawati & Wulandari, 2019).

Problems or solutions in mathematical literacy encompass three dimensions: context, mathematical content, and mathematical process. Context refers to the setting of a specific problem (Demir & Altun, 2018). According to the definition provided by the Programme for International Student Assessment (PISA), each problem has its own context, which can be: (1) personal, (2) occupational, (3) societal, or (4) scientific. Mathematical content refers to the knowledge of mathematical concepts that students need to approach a problem. It includes four categories: (1) quantity, (2) space and shape, (3) change and relationships, and (4) uncertainty and data. Mathematical processes involve actions students take when solving a problem. These processes can be classified into three categories: (1) formulating situations mathematically; (2) employing mathematical concepts, facts, procedures, and reasoning; and (3) interpreting, applying, and evaluating mathematical outcomes (OECD, 2016).

In the Thai context, Khwannan (2014) developed a mathematical literacy evaluation model. This model encompasses mathematical problem-solving in real-world situations, mathematical content knowledge, traditional mathematical competency, and mathematical competency in problem-solving. Mathematical problem-solving in real-world situations refers to the ability to solve problems in personal, educational, societal, occupational, scientific, and mathematical contexts. Mathematics content knowledge involves understanding quantity, space, shape, change and relationships, and uncertainty. Traditional mathematical competency includes mathematical thinking and reasoning, arguments, communication, presentation, mathematical questioning, problem-solving, representation, language, operation, and mathematical tools. Lastly, mathematical competency in problem-solving involves applying mathematical problem-solving skills to solve new problems, make connections, reflect, and communicate both answers and processes. This research revealed that all four factors had construct validity in the Thai students' context. Therefore, this mathematical literacy construct serves as a conceptual framework for measuring variables in this study.

Mathematical Problem-Solving

Mathematical problem-solving refers to the strategies employed to determine which steps to take and how to address a particular mathematical problem (Göktaş & Yazıcı, 2020; Li & Disney, 2021; Piñeiro et al., 2021). As proposed by Polya (1957), mathematical problem-solving comprises four steps: understanding the problem, devising a plan, carrying out the plan, and looking back. Additionally, Posamentier and Krulik (1998) suggest that mathematical problem-solving involves eight steps: (1) intelligent guessing and testing (including approximation); (2) solving a simpler analogous problem; (3) animation and simulation; (4) working backward; (5) finding a pattern; (6) logical reasoning; (7) making a drawing (visual representation); and (8) adopting a different point of view. In the Thai context, numerous educational researchers have adopted Polya's approach. For example, Surawanichakun and Thongmoon (2019) used Polya's approach to design learning activities aimed at enhancing mathematical problem-solving abilities. Similarly, Kummod and Art-In (2019) combined the open approach with Polya's problem-solving to improve mathematical problem-solving abilities. Additionally, Mola et al. (2020) integrated the inquiry cycle with Polya's approach to enhance mathematical problem-solving abilities. Furthermore, Amara (2018) developed a mathematical problem-solving test based on Polya's approach (1957), covering four steps of understanding the problem, devising a plan, carrying out the plan, and looking back. Thus, Polya's problem-solving processes have significantly influenced mathematical problem-solving in the Thai educational context and are widely recognized as effective strategies.

METHODOLOGY

Research Design

This research employed a true experimental pre-test and post-test control group design. This design is commonly employed to evaluate teaching models when there are multiple sample groups, and learning outcomes are measured with random assignment. It was deemed appropriate for this research as it aimed to investigate the effectiveness of teaching models and compare the outcomes based on specific criteria. Therefore, this research design allowed for a more accurate analysis of the dependent variables (mathematical literacy and mathematical problem-solving), which were the results of the teaching models (STEMEN and 5E teaching models) and minimized potential influences of extraneous variables.

Sampling and Procedure

The study utilized a true experimental design, with learners randomly assigned to experimental and control groups. Initially, random selection was carried out during the sampling process, followed by random assignment. A total of 70 Grade 9 students were randomly selected from a pool of 156 students at a secondary school in Phayao, Thailand, during the second semester of the 2020 academic year. Subsequently, the sample was randomly allocated to an experimental group (STEMEN teaching model: n=35) and a control group (5E teaching model: n=35) using a coin flip.

The most vital processes involved in this study were random selection and random assignment. Random selection is a sampling method that adheres to the principles of objectivity, non-bias and equality, and is carried out through systematic sampling. By adopting this method, the study selected the participants based on their mathematical knowledge, ensuring equal opportunities for all individuals to be selected through probability. As a result, a total sample of 70 participants was obtained. Subsequently, random assignment was conducted, with the sample divided into two groups: experimental group and control group, each with 35 participants. The implementation of this method resulted in significant changes in dependent variables, including mathematical literacy and mathematical problem-solving, which were primarily attributable to the independent variables (specifically the teaching models, i.e. STEMEN and 5E teaching models) and minimally affected by extraneous variables. This contributed to the study's internal validity. Ensuring that the selected sample was representative of the population potentially enabled the results to be generalized to other populations or relevant contexts, thereby achieving external validity. In simple terms, random selection helped establish external validity, enabling the results of the study to be generalized to other populations. Random assignment, on the other hand, helped establish internal validity, enabling the researcher to conclude the effect of the interventions. Hence, random selection and random assignment are distinct processes that should be conducted to ensure the external and internal validity of the study.

Intervention Processes

(1) *STEMEN teaching model*

The STEMEN teaching model was developed by combining the STEM approach with the educational neuroscience approach. Its content validity was evaluated by five educational experts from the University of Phayao. The teaching model was then improved based on the experts' recommendations as follows: (1) each syntax of the developed teaching model should clearly demonstrate the combination of STEM education and educational neuroscience; (2) the name of the teaching model should be concise and accurately portray the integration of these two approaches; and (3) it may not be necessary to specify the measurement and evaluation of specific dependent variables, as the STEMEN teaching model may be applicable to address problems or enhance the capabilities of other variables, which should be investigated in the future. These processes determined the teaching procedures for the STEMEN teaching model. Additionally, the following four areas were discussed to improve the STEMEN teaching model. 1) Accuracy of knowledge: It was concluded that the STEMEN teaching model was theoretically well-founded, appropriate, and modern. 2) Appropriateness: The model was well-suited to the learners and the educational institution's context, provided clear directions for practical application, and could be used to develop lessons effectively. 3) Feasibility: The model had clear objectives, a well-defined syntax and served as a guideline for developing lesson plans, effectively translating the curriculum's ideology into classroom teaching activities. 4) Practical guidance: The model could provide practical suggestions to teachers in designing learning activities and managing the learning environment effectively. These issues were discussed by a panel of five qualified experts in curriculum and instruction. Following this, a meeting with all the experts was held to assess the face validity of the four areas aspects in question. It was concluded that the developed teaching model was excellent and feasible for practical application. Therefore, the STEMEN teaching model could be applied in classrooms. To validate the STEMEN teaching model, the researchers implemented it by teaching statistics in a mathematics subject for two hours per week over five weeks using a one group pre and post-test design. The samples used in this process were distinct from the samples used in the main research. The results showed that the average post-test scores in mathematical literacy and mathematical problem-solving were higher than the pre-test scores. With the true experimental design, the differences in learning outcomes, namely mathematical literacy and mathematical problem-solving, could be compared. The research hypothesis was tested on two teaching models, particularly the STEMEN teaching and the 5E teaching model.

The STEMEN teaching model comprises two principles as follows: (1) the integration of four disciplines (science, technology, engineering, and mathematics) affecting changes in genes, neural activity, the brain, the body, and the environment, and the interaction of all constraints; (2) two dimensions of the teaching model, including syntax and the technological learning environment.

Regarding Dimension 1, the STEMEN teaching model consists of seven syntaxes: Syntax 1) Entertainment: Enhances and stimulates learners' emotional climate with real-world environment and situation problems. Syntax 2) Enclosure: Establishes links between cognitive models related to problem-solving and analysis. Syntax 3) Encounter: Involves conducting investigations through proactive activities and utilize content, skills, and concepts to evaluate ideas related to the environment and design ideas. Syntax 4) Ensuring: Learners analyse and assess collected data, locating optimal design solutions using their knowledge. Syntax 5) Encompassment: Applies mathematical knowledge to provide explanations, tests various phenomena, makes predictions, and identifies relationships between variables to design solutions and prototypes. Syntax 6) Enhancement: Utilizes knowledge, solutions, and models to improve, construct and design solutions based on the environmental context. Syntax 7) Enlightenment: learners present their arguments with empirical evidence to locate the optimal solution and subsequently refine the solution for the next cycle.

As for Dimension 2, the technological learning environment comprised two principles: 1) diversity of technology learning environment, including both concrete and abstract objects; 2) open access channels for scaffolding STEMEN procedures. These principles were employed to promote learning by doing.

(2) *5E teaching model*

The 5E teaching model (5E) is typically utilized to design scientific learning activities in Thailand and is promoted for use in public schools by the Institute for the Promotion of Teaching Science and Technology (IPST) (2012). For this reason, this research adopted the 5E inquiry model (5E) for the control group. The model consists of five phases: Engage, Explore, Explain, Elaborate, and Evaluate. It assumes that learning should be acquired through active learning, not passive learning. That is, students' development should be spurred by analysis, evaluation, inquiry, and collaborative learning, as these methods enable them to develop a better understanding and retain their knowledge. Knowledge can be developed through questions, observation, analysis, explanation, conclusion, and new inquiries (Institute for the Promotion of Teaching Science and Technology, 2012).

Among five phases in the 5E teaching model, the Engage phase focuses on introducing a lesson, increasing learners' motivation and curiosity about the current situation. This step clarifies the issues to be studied as specified in the curriculum objectives. Next, the Explore phase involves understanding the issues being studied through learning by doing, conducting experiments, hands-on practices, and research to gather information for the next step. Following this, the Explain phase entails using the collected data to analyze, interpret, summarize, and present the results in the form of tables, texts, drawings, and charts. The results produced in this stage can support or reject the proposed hypothesis, with the essential point being that they should provide a new body of knowledge and enhance learners' understanding. Next, the Elaborate phase involves connecting new knowledge with background knowledge or novel ideas that have been researched. Additionally, learners should draw conclusions to justify related situations or events, thereby enhancing their knowledge. Finally, the Evaluate phase entails assessing both the learning processes and learning outcomes using various assessment tools to improve learners' knowledge and their ability to apply this new knowledge in other contexts.

The pre-test and post-test assessed two learning outcomes: mathematical literacy and mathematical problem-solving. Both teaching models, STEMEN and 5E, were implemented to teach statistics in mathematics for two hours per week over five weeks. The former was implemented in the experimental group, while the latter was employed in the control group. This study aimed to compare learning outcomes in mathematical literacy and mathematical problem-solving between the STEMEN and 5E teaching models.

Research Instrument

Two tests were used in this study: mathematical literacy test and mathematical problem-solving test.

(1) *Mathematical literacy test*

Khwannan (2014) mathematical literacy test was used to measure students' mathematical literacy in this research. The test consisted of 49 items (54 marks in total) and lasted 60 minutes. Each correct answer was awarded 1 point while an incorrect answer was awarded 0 point. The difficulty index value ranged from 0.32 to 0.79, the discrimination index value was between 0.21–0.64, and the reliability value was 0.96 (Khwannan, 2014). It covered six types of questions as follows.

(1.1) Multiple choice (10 items)
The difficulty index value was between 0.32–0.75, with the discrimination index value between 0.21–0.57. This indicated that all test items were of acceptable quality (Khwannan, 2014). The following is an example of a test question.

26. Situation: Mr. Phum broke open a money box and found 5 baht and 10 baht coins, amounting to 200 coins. The sum exceeds 1,200 baht but is less than 1,600 baht.

Figure 1

A Money Box

Item 26: Find out the maximum amount of money in the money box. (1 mark)
A. 1,599 baht
B. **1,595 baht**

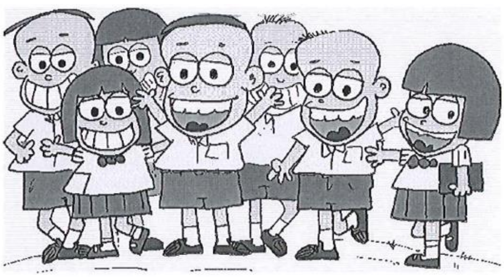
C. 1,590 baht
D. 1,585 baht

(1.2) complex multiple choice (5 items)
The difficulty index value was between 0.50–0.79, and the discrimination index value ranged from 0.29 to 0.43, indicating the acceptable quality of all test items (Khwannan, 2014). The following is an example of a test question.

14. Situation: Grade 7 students at a school.

Figure 2

Primary Students



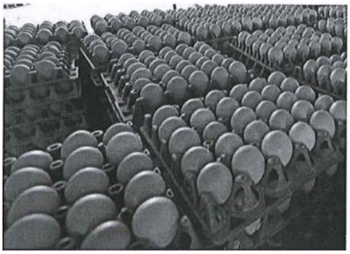
Item 14: Female students account for 7 out of 15 Grade 7 students in a class. Assuming the class consists of 450 students, circle the correct answer for each of the following statements.
(4 marks)

A. There are 210 female students.	**True**/False
B. Male students account for 8 out of 15 students in the class.	**True**/False
C. There are 210 male students.	True/**False**
D. There are 250 male students.	True/**False**

(1.3) responses related (2 items)
The difficulty index value ranged between 0.68–0.75, and the discrimination index value was between 0.21–0.50, showing that all test items were of acceptable quality (Khwannan, 2014). The following is an example of a test question.
4. Situation: A merchant purchased 500 eggs, each at the price of 1.45 baht.

Figure 3

Egg Cartons



Item 4: A. If he/she wants to earn a profit of 240 baht, each egg should be sold at ………. baht.

B. However, selling each egg for 1 baht will result in a loss of ………….. baht.

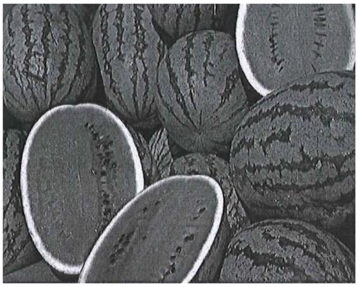
(2 marks)
Answer for item A: 1.93 baht
Answer for item B: 225 baht

(1.4) open constructed response (10 items)
The difficulty index value ranged from 0.54 to 0.79, and the discrimination index value ranged between 0.21–0.64, suggesting that all test items achieved acceptable quality (Khwannan, 2014). The following is an example of a question.

16. Situation: Boom and Bas sell watermelons at the market every day. Each of them sells 30 watermelons, with Boom selling at a price of two pieces for 50 baht and Bas selling at a price of three pieces for 70 baht.

Figure 4

Watermelons



Item 16: One day, Bas was busy and could not sell watermelons, so he asked Boom for help. So, Boom gathered the watermelons and sold them at a price of 5 pieces for 120 baht. Is the total revenue earned from selling watermelons the same when sold separately compared to when sold together? Why? (2 marks)

A. Full score = 2
Answer: "Not the same," accompanied by an explanation.
- It is not the same because selling separately results in relatively greater revenue, compared to selling together.
B. Partial score = 1
Answer: "Not the same", but an explanation is not provided or the reason given is incorrect.
C. No score = 0
Answer: Other answers or no answer.

(1.5) close constructed response (19 items).
The difficulty index value was between 0.57–0.79, and the discrimination index value ranged from 0.21 to 0.64; it showed that all test items attained acceptable quality (Khwannan, 2014). The following is an example of a question.

3. Situation: Three ropes, each with lengths of 231, 147, and 252 meters, are cut into the longest pieces of equal length possible. At what length should each piece of rope be to ensure no leftover pieces?

Figure 5

Ropes

Item 3: If three ropes are cut into the longest pieces of equal length, at what length should each piece be to avoid any leftover pieces? (1 mark)

Answer: Each rope should be cut into pieces, each with a length of 21 meters.

(1.6) short answer (3 items).
The difficulty index value was between 0.64–0.71 while the discrimination index value ranged between 0.36–0.64, indicating that all test items were of acceptable quality (Khwannan, 2014). The following is an example of a question.

15. Situation: A certain road is 120 kilometers long.

Figure 6

Road

Item 15: ¾ of the entire length of the road has been paved with concrete. What is the remaining length of the road which is yet to be paved? (1 mark)
Answer: ¼ of the road is paved with concrete, or 30 kilometers of the road remain unpaved

(2) *Mathematical problem-solving test*

Amara (2018)'s problem-solving test was employed to measure students' problem-solving skills. The test was in a multiple-choice format with 36 question items (36 marks in total), which lasted 90 minutes; each correct answer and incorrect one would be marked as 1 and 0 point, respectively. The index of objective congruence was between 0.67–1.00, the difficulty index value was in the range of 0.25–0.79, the discrimination index value ranged from 0.21–0.77, and the reliability value was 0.93 (Amara, 2018).
This test was derived from Polya's theoretical concept and aimed to measure four factors listed as follows.

(2.1) Understanding the problem (9 items): The difficulty index value ranged from 0.65 to 0.79, and the discrimination index value was between 0.21–0.58. An example is given as follows (Amara, 2018).
Instructions: Use the information in situation (I) to answer questions (I).
Situation (I)
A certain swimming pool has a length of the pool's edge of 15 meters and a width of 13 meters. Assuming you want to fill it with 780,000 liters of water, how high would the water level be from the bottom of the pool?
(I) Based on the scenario (0) given, what information do you think this problem seeks?
A. What is the length of the pool's edge?
B. What is the width of the pool's edge?
C. How many liters of water does the pool contain?
D. How high is the water level from the bottom of the pool?

(2.2) Devising a plan (9 items): The difficulty index value was between 0.59–0.73, and the discrimination index value was between 0.26–0.45. An example is shown as follows (Amara, 2018).

(II) In situation (0) provided, which formula can be used to find the answer?
A. Volume of a rectangular prism = Width x Length x Height
B. Volume of a cylinder =
C. Volume of a pyramid = x Base area x Height
D. Volume of a cone =

(2.3) Carrying out the plan (9 items): The difficulty index value was in the range of 0.54–0.63, and the discrimination index value was between 0.25–0.62. An example of the question is provided as follows (Amara, 2018).
(III) Based on the given scenario (0), how high do you think the water level would be?
A. 2 meters
B. 4 meters
C. 52 meters
D. 60 meters

(2.4) Looking back (9 items): The difficulty index value ranged from 0.25 to 0.37 while the discrimination index value ranged between 0.37–0.77. The following is an example of the question (Amara, 2018).
(IV) Considering the given scenario (0), in what way can the answer be checked?

A. 780 = 15 x 13 x 2
B. 780 = 15 x 13 x 4
C. 780 = 15 x 13 x 52
D. 780 = 15 x 13 x 60

Data Analysis

In this research, the difference in mean scores for mathematical literacy and mathematical problem-solving between the two groups was tested. Consequently, the researchers analyzed mathematical literacy and mathematical problem-solving, comparing the mean of the total linear combination between both groups using two types of statistics. Specifically, two basic statistics were used to describe general data: mean (M) and standard deviation (S.D.). These were used to analyze descriptive data. Additionally, repeated measures ANOVA with Wilks' lambda was employed to analyze the mean comparison for mathematical literacy and mathematical problem-solving between the two independent groups (Tabachnick & Fidell, 2013).

RESULTS

The results of this research are presented according to the objectives of the study. The first finding reports the differences in mathematical literacy and mathematical problem-solving of Grade 9 students before and after the implementation of the STEMEN and 5E teaching models in classrooms. This is followed by an evaluation of the effect of the two models on the students' mathematical literacy and mathematical problem-solving.

Findings on Mathematical Literacy

Mathematical literacy (ML) was also measured based on accuracy scores. The mean scores (M) and standard deviation (SD) of both the pre-test and post-test, measured by the mathematical literacy test, for both the experimental and control groups are shown in Table 3.

Table 3

Mean Scores (M) and Standard Deviations (SD) of Mathematical Literacy in Both the Experimental and Control Groups

ML	STEMEN teaching model				5E teaching model			
	Pre-test		Post-test		Pre-test		Post-test	
	M	SD	M	SD	M	SD	M	SD
Total score	10.37	4.54	20.43	5.85	10.49	4.31	13.80	3.48

According to Table 3, it is evident that in the experimental group (using STEMEN teaching model), the post-test mean score for mathematical literacy (M=20.43, SD=5.85) exceeded the pre-test mean score (M=10.37, SD=4.54). Similarly, in the control group (using the 5E teaching model), the post-test mean score for mathematical literacy (M=13.80, SD=3.48) surpassed the pre-test mean score (M=10.49, SD=4.31). Subsequently, further analysis was conducted to investigate the effectiveness of the STEMEN teaching model in enhancing mathematical literacy between the experimental and control groups, as shown in Table 4.

Table 4

Multivariate Tests for Mathematical Literacy

Effect	Mean square	F	df_1	df_2	p	n_ρ^2
Between groups						
Model	371.31	9.63	1	68	0.00	0.12
Within groups						
Time	1564.46	374.97	1	68	0.00	0.85
Model x Time	397.83	95.35	1	68	0.00	0.58

In Table 4 below, the multivariate test (Wilk's lambda) for mathematical literacy was significant, indicating that the teaching models significantly influenced mathematical literacy (F[1,68]=9.63, p=0.00) and accounted for 12 percent of the variance of mathematical literacy (n_ρ^2 =0.12). Time was found to have a significant influence on mathematical literacy (F[1,68]=374.97, p=0.00) and accounted for 85 percent of the variance of mathematical literacy (n_ρ^2 =0.85). Moreover, the teaching models had a significant interaction with time (F[1,68]=95.35, p=0.00) and explained 58 percent of the variance of mathematical literacy (n_ρ^2 =0.58).

Findings on Mathematical Problem-Solving

Mathematical Problem-Solving (MPS) was also measured by accuracy scores. The pre-test and post-test mean scores (M) and standard deviation (SD) measured by the mathematical problem-solving test of the experimental and control groups are shown in Table 5.

Table 5

Mean Scores (M) and Standard Deviations (SD) of Mathematical Problem-Solving in the Experimental and Control Groups

MPS	STEMEN teaching model				5E teaching model			
	Pre-test		Post-test		Pre-test		Post-test	
	M	SD	M	SD	M	SD	M	SD
Total score	17.57	7.24	27.23	5.27	18.06	5.22	19.20	4.70

In the experimental group (using the STEMEN teaching model), the post-test mean score for mathematical problem-solving (M=27.23, SD=5.27) outperformed the pre-test mean score (M=17.57, SD=7.24) as shown in Table 5. Similarly, in the control group (using the 5E teaching model), the post-test mean score exceeded the pre-test mean score (M=18.06, SD=5.22). Subsequently, further analysis was carried out to explore the effectiveness of the STEMEN teaching model in enhancing mathematical problem-solving between the experimental and control groups, as shown in Table 6.

Table 6

Multivariate Tests for Mathematical Problem-Solving

Effect	Mean square	F	df_1	df_2	p	n_ρ^2
Between groups						
Model	497.83	8.39	1	68	0.01	0.11
Within groups						
Time	1020.60	188.55	1	68	0.00	0.74
Model x Time	634.31	117.18	1	68	0.00	0.63

In Table 6, the multivariate test (Wilk's lambda) for mathematical problem-solving was significant. This suggests that the teaching models had a significant influence on mathematical literacy (F[1,68]=8.39, p=0.01) and accounted for 11 percent of the variance in mathematical literacy (n_{ρ}^{2} =0.11). Furthermore, time significantly influenced mathematical problem-solving (F[1,68]=188.55, p=0.00), explaining 74 percent of the variance in mathematical problem-solving (n_{ρ}^{2} =0.74). Additionally, there was a significant interaction between teaching models and time (F[1,68]=117.18, p=0.00), which explained 63 percent of the variance in mathematical problem-solving (n_{ρ}^{2} =0.63).

In reference to Tables 5 and 6, it can be observed that the STEMEN teaching model influenced the variance of mathematical literacy (n_{ρ}^{2}=0.12) more than the variance of mathematical problem-solving (n_{ρ}^{2}=0.11). Additionally, time had a relatively greater influence on the variance of mathematical literacy (n_{ρ}^{2}=0.85), compared to the variance of mathematical problem-solving (n_{ρ}^{2}=0.74). More importantly, the teaching models significantly interacted with time, influencing the variance of mathematical literacy (n_{ρ}^{2}=0.58) less than the variance of mathematical problem-solving (n_{ρ}^{2}=0.63).

DISCUSSION

The findings of this research revealed that the STEMEN teaching developed through a combination of the STEM education approach and an educational neuroscience approach, effectively fosters an in-depth understanding of instructional processes and designs. First, the traditional approach, i.e., the 5E teaching model, incorporates science, technology, engineering, and mathematics into classrooms (Kelly & Knowles, 2016; Li et al., 2020). Meanwhile, educational neuroscience is a new paradigm that encompasses concepts and knowledge about learning, derived from the growth of neuroscience research on learning processes (Colón-Rodríguez et al., 2019; Margot & Kettler, 2019). Two approaches were combined to construct the STEMEN teaching model, which was found to enhance mathematics literacy and mathematical problem-solving. These skills are regarded as essential abilities in the digital age and must be instilled in children worldwide (Bolstad, 2020; Göktaş & Yazıcı, 2020; Rizki & Priatna, 2019). Therefore, the present study successfully investigated modern learning theory to develop a new and more effective teaching model suited to the educational context.

The results of this study highlighted the effectiveness of the STEMEN teaching model in improving students' mathematical literacy and mathematical problem-solving. Based on empirical evidence, it is hoped that the developed model can be implemented to enhance students' learning outcomes in general classroom contexts. The findings of this research suggest that the STEMEN teaching model can improve students' learning outcomes. Consequently, it is advised that teachers use the STEMEN teaching model in their classrooms since it has been proven effective in enhancing mathematical literacy and mathematical problem-solving. Teaching through the STEMEN teaching model should be centered on two dimensions: syntax and the technological learning environment. Specifically, syntaxes consist of: (1) Entertainment, (2) Enclosure, (3) Encounter, (4) Ensuring, (5) Encompassment, (6) Enhancement, and (7) Enlightenment. All syntaxes were constructed based on the STEM education approach and the educational neuroscience approach. STEM education is widely utilized in classrooms because teachers believe that this approach can promote the learning of 21st-century skills (Margot & Kettler, 2019; Penprase, 2020), increase students' innovative ability (Corlu et al., 2014) and cultivate sophisticated thinking skills (Uttal & Cohen, 2012). Despite its practical applications, there is a need for further development of STEM education. Educational neuroscience is employed to develop a new teaching model because it is believed to facilitate the creation of educational innovations (Goswami, 2016; Norwich, 2015; Srikoon, 2023). The technological learning environment consists of two parts: a diversity of technology learning environments and channels for scaffolding STEMEN procedures, which facilitate learning by doing. Both dimensions were derived from Kelly and Knowles's (2016) STEM education, Hardiman's (2012), and Westermann et al.'s (2007) educational neuroscience. Therefore, the STEMEN teaching model is an interdisciplinary teaching model that integrates both STEM education and education neuroscience principles.

The primary reason the STEMEN teaching model can enhance learners' learning outcomes lies in the creation and stimulation of an emotional climate through real-world environment and situation problems. With a suitable emotional climate, the sensory register is activated, increasing the ability to perceive more information, which is described as attention to information processing (Sweatt, 2010; Hardiman, 2012; Srikoon et al., 2017). This contributes to improving working memory and storing knowledge in long-term memory. In other words, with increasingly effective attention and working memory, learning outcomes are enhanced (Sousa, 2006; Srikoon, 2020; Srikoon, 2021a). Moreover, cognitive training based on educational neuroscience is associated with mathematic abilities (Gola et al., 2022; Lee & Bull, 2016; Srikoon & Punsrigate Khonjaroen, 2020).

The STEMEN teaching model grounded in modern psychology and cognitive development, is expected to develop mathematical literacy and mathematical problem-solving skills. This allows students to acquire thinking abilities, problem-solving skills, and other 21st century skills (Lee & Bull, 2016; Srikoon & Punsrigate Khonjaroen, 2020).

Educational neuroscience is an interdisciplinary science focused on developing teaching models (Hardiman, 2012; Srikoon, 2021a). These processes are used to design innovations based on novel concept theories and in-depth explanations to improve pedagogy (Feiler & Stabio, 2018; Westermann et al., 2007). Additionally, incorporating educational neuroscience in learning can enhance teaching effectiveness and students' learning outcomes (Goswami, 2016; Sousa, 2006).

In conclusion, educational development has progressed. The findings of this study provide insights into educational neuroscience and STEM education. Using educational neuroscience for teaching model development can help design teaching innovations for classroom practices and offer guidelines for in-class applications. It is suggested that teachers enhance their understanding of educational neuroscience and STEM education, as these contribute to the design of instructional activities. Therefore, they should collaborate to find innovative ways for classroom development by drawing on theories of educational neuroscience and STEM education to develop learning activities.

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ETHICAL APPROVAL

Ethics approval and consent to participate was granted by the University of Phayao Human Ethics Committee (Project No. 2.2/019/63). Informed consent was obtained from all student participants in line with the ethical approval.

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