frontiers | Research Topics

Advances in the contributions of mathematics in the field of education and psychology

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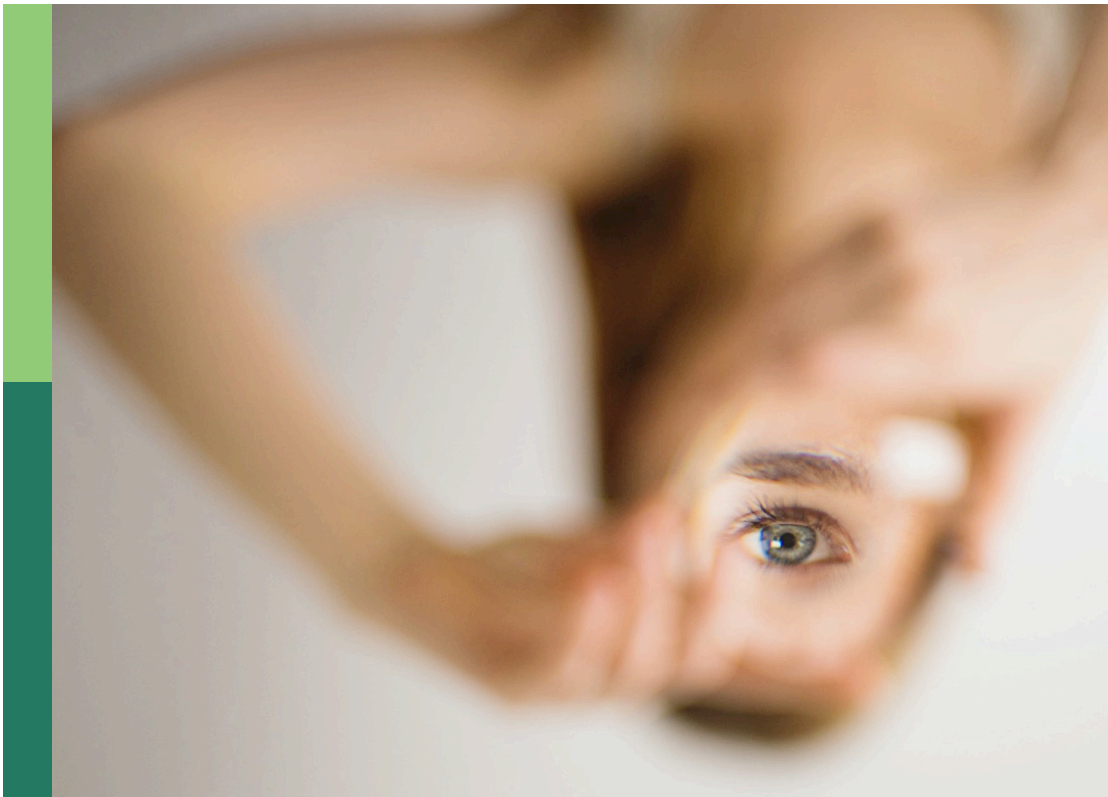

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Advances in the contributions of mathematics in the field of education and psychology

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Editorial: Advances in the contributions of mathematics in the field of education and psychology

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educational psychology, affective domain, mathematics, mathematical performance, mathematics education

Editorial on the Research Topic
Advances in the contributions of mathematics in the field of education and psychology

Over the past decades, researchers have been investigating mathematics education and exploring factors associated with achievement in mathematics. Although one might assume that mathematics education and its positive outcomes are primarily linked to cognitive factors, such as spatial ability, critical thinking skills, or executive functioning, it is not understood without considering affective factors and their influence (Higbee and Thomas, 1999; Gómez Chacón, 2000). Nowadays, mathematics teaching is perceived as a multifaceted process influenced by a wide variety of factors such as students' self-concept, attitudes toward mathematics, mathematics anxiety, perceptions of the usefulness of mathematics, or motivation (Suárez-Álvarez et al., 2014). These variables may be related to different aspects involved in the teaching-learning situation, such as the teacher, the school, the family, or the student (Algani and Eshan, 2019). Therefore, mathematics education requires the efforts of educators and researchers to obtain an in-depth understanding of this complex process to reduce or eliminate the impact of cognitive and non-cognitive barriers to learning mathematics. The articles presented in this Research Topic address these issues from diverse perspectives.

This Research Topic opens with a study conducted by Xu and Qi, focusing on the mathematical problem-solving ability of middle school students in the compulsory education stage and the factors influencing their performance. The authors analyzed students' problem-solving competence by examining the impact of factors related to the school environment, such as location (urban or rural) and the teaching method. Additionally, they explored student-related factors, including self-efficacy and mathematics anxiety. The Research Topic continues with the study by Wang et al., which examines the impact of high school students' mathematical attitude determinants (attitude, subjective norms, and perceived behavioral control) on intentions, behavioral engagement, and mathematical performance. This study uses and extends the Theory of Planned Behavior (TPB) framework by incorporating mathematical performance. Using a different approach, Ramos-Galarza et al. carried out an intervention involving a program of Brain Gym exercises designed to enhance the learning of these key mathematical concepts among high school students. These concepts included the definition of rational numbers, problem-solving abilities, mathematical order relationships, and equivalent fractions. The authors aimed to improve the learning process through systematic exercises that stimulated neural connections between cerebral hemispheres.

The discussion of the topic progresses with Ling and Mahmud's study focused on sentence-based mathematical problem-solving skills. They used a qualitative research approach to detect challenges faced by teachers and the approaches they employ in addressing these challenges when teaching sentence-based mathematical problem-solving skills to primary school students. Exploring another element and its influence on mathematical education, Li et al. focused on studying the effect of Chinese family income on the intergenerational transmission of education using data provided by the China Family Panel Studies (CFPS). The authors further extend their analysis by examining whether the university expansion policy could alleviate potential differences in access to education motivated by the level of family income. Continuing with the topic, Yu et al. presented a study aimed at investigating how to measure mathematical self-efficacy meaningfully. For this purpose, they employed a multi-trait and multi-method design that included three traits (number and algebra, graphics and geometry, and synthesis and practice) and three methods to discuss [general-math-task-referenced self-efficacy, unconventional-math-problem-referenced self-efficacy, and Motivated Strategies for Learning Questionnaire (MSLQ) self-efficacy]. To verify the validity of the design, the authors constructed a confirmatory factor analysis (CFA) model.

Exploring student-related factors in the mathematics teaching-learning process, Puusepp et al. examined the development of potential associations between the mindset of primary school students and the attentional neural processing shown by students when receiving feedback on their mathematical performance. This feedback, whether positive or negative, has an impact on students that may depend, among other factors, on their beliefs and mindsets. To gain a better understanding of these student mindsets, neuroscientific research is employed, allowing the analysis of neural processes associated with the perception and cognition of feedback, avoiding limitations found in other data collection tools. Addressing the factors related to the methodology used in the mathematics classroom, Hui and Mahmud carried out a systematic literature review based on the PRISMA methodology and focused on game-based learning in mathematics education. This survey covered the influence of this teaching methodology on both the cognitive and affective domains. The topic persists in examining methodologies in this case to enhance the mathematical reasoning of elementary school students. The study conducted by Mahmud and Mohd Drus aimed to explore different types of oral questions used with elementary school students and their potential advantages in helping students improve their mathematical skills and reasoning.

Continuing the search for factors related to schools, students, and their families that affect students' mathematic outcomes, Molina-Muñoz et al. carried out an analysis of the potential impact that students' psychological and emotional factors may have on their mathematical literacy. The authors analyzed data from the Spanish sample of the 2018 edition of the Programme for International Student Assessment (PISA) using multilevel regression models. This allowed them to assess which factors had a positive Impact on students' mathematical competence and which resulted in a negative impact. Hernández de la Hera et al. focused on studying the possible causes that lead to the rejection of mathematics by high school and university students and their demotivation. They analyzed the relationships between attitudes toward mathematics, attitudes toward statistics, mathematical anxiety, and student self-efficacy, employing an artificial neural network for the backpropagation algorithm capable of predicting academic performance. Furthermore, based on the results obtained, they analyzed the implications these would have on mathematical education. The research proposed by Chen and Moc continued the quest for factors influencing learning by focusing their analysis on motivation and perceived family involvement among high school students. The study aimed to examine how these two factors relate to students' ability to cope with difficulties and challenges in their daily school life, using structural equation modeling. The Research Topic concludes with an article by Yu, who presented a systematic literature review focused on identifying key aspects and knowledge related to the neuroscientific basis of mathematical cognitive impairment and anxiety and their influence on educational practices, highlighting the interaction between cognitive processes and educational outcomes. In addition, this proposal provides suggestions for new strategies to practically address students' mathematic anxiety and cognitive impairments.

The contributions in this Research Topic provide a better understanding of the teaching and learning process of mathematics at various educational levels and the numerous factors influencing this process, related to aspects such as methodology, family, or the emotional dimension of the student. Additionally, the topic addresses aspects such as the analysis of methodologies, the neuroscientific basis, or proposing a measurement tool. Nevertheless, new issues arise that need to be addressed. For instance, it would be interesting to expand previous research on different aspects of the affective domain, such as anxiety toward mathematics, not only in students but also in teachers who already teach mathematics. The teacher's role is crucial for understanding the teaching-learning process. This Research Topic highlights new insights and explores additional aspects of mathematical education. Additionally, it raises new questions to advance the ongoing efforts in understanding the teaching and learning of mathematics, which is crucial for present society and even more so for future society.

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Middle school students' mathematical problem-solving ability and the influencing factors in mainland China

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This study investigated the mathematical problem-solving ability of 42,644 ninth-grade students who participated in regional education quality health monitoring from Z province in East China and the factors which influence their performance of mathematical problem-solving. The results are as follows: (1) ~96% of the students' mathematics problem-solving ability meets the basic academic requirements of the mathematics curriculum standards; (2) boys and children without siblings performed better, and urban students performed significantly better than county and rural students; (3) ~28% of students' mathematical problem-solving performance came from inter-school variability; urban and rural backgrounds had a greater impact on mathematical problem-solving than did teaching factors, while teaching self-efficacy had the least impact among the school-level influencing factors. In contrast, the influence of individual non-intelligence factors was higher than that of student background variables, including a greater positive effect of self-efficacy and a greater negative effect of mathematics anxiety.

KEYWORDS
influencing factors, mathematical problem-solving, middle school mathematics, mainland China, benchmark, proficiency

Introduction

Problems inspire the search for knowledge and learning. As such, Zhang (2012) suggests that personal learning and knowledge acquisition are pursued to solve practical difficulties. Thus, the purpose of mathematics learning is to solve various problems in the mathematical context (Ma, 2009). The role of science is not only to explain the different phenomena in the world, but also to solve real-world problems. Thus, problems drive scientific development. Historically, mathematical science developed from two cultural traditions and two models. Culturally, mathematics is derived from Western abstract deductive mathematics represented by ancient Greek mathematics and algorithmic applied mathematics represented by ancient Chinese mathematics (Liu, 2005). The confluence of these two traditions, neither of which can be solved without mathematical constructs, formed modern mathematics. Polya (1944) argued that one of the main purposes of mathematics education is to develop students' problem-solving ability and teach students how to think. The indispensable role of the ability to solve problems using mathematics in the process of mathematical exploration, discovery, and innovation has gradually attracted widespread global attention. Mathematical problem-solving ability has been introduced into global curriculum reforms (National Council of Teachers of Mathematics (NCTM), 1980; Ministry of Education of the People's Republic of China, 2012; Wang, 2021) and international evaluations (OECD, 2013). In addition, scholars from the East and West have focused on the important factors that influence students' performance of mathematical problem-solving. They can be broadly summarized as internal factors of the individual learner (e.g., cognitive resources, meta-cognition and non-intellectual factors), external factors (e.g., complexity, familiarity, type, context of the problem), and teaching factors (Schoenfeld, 1985; Mayer, 1992). But generally speaking, at present, the academic community have not paid enough attention to the non-intellectual factors and teaching methods (Wang, 2000). Moreover, comparisons reveal that American mathematics education promotes the development of students' mathematical literacy or other core abilities, wherein the problem-solving process focuses on the application of mathematics knowledge and skills. In contrast, Chinese mathematics education has long advocated *double-base teaching*, which promotes a process of mathematical problem-solving that focuses on the acquisition of basic knowledge and skills instead of reasoning activities (Peng et al., 2017). While numerous studies suggest that Chinese and East Asian students' overall math problem-solving skills surpass those of Western students, such as those in the United States, various studies indicate that no significant gap exists between the two in solving complex mathematical problems (Zhao and Shen, 2003). In fact, the higher mathematics achievement of middle school students in mainland China is inextricably linked with the learning process of mathematical problem solving. In particular, China's compulsory education middle school mathematics curriculum standard also emphasizes that students should cultivate mathematical affections in mathematics learning and actively exert the important promotion of non-intelligence factors (Ministry of Education of the People's Republic of China, 2012). Thus, under the advocacy of domestic *double-base teaching*, how do Chinese students develop their mathematical problem-solving ability? Which factors have a greater impact on it? These questions still urgently require an intensive investigation of the overall mathematical problem-solving process of mainland Chinese students, especially to determine the key internal and external factors that influence their mathematical problem-solving performance.

Literature review

Significance and value as goals of mathematics teaching

The advantage of improving problem-solving ability as a goal of mathematics teaching has long been recognized. Since the 1980s, most countries have regarded improving students' problem-solving ability as one of the primary goals of mathematics teaching (Silver and Kilpatrick, 1988; Kilpatrick, 2009). For instance, in 1980, the National Council of Teachers of Mathematics (NCTM) proposed establishing problem-solving as the core of the mathematics curriculum, thereby introducing a primary goal of American mathematics education [National Council of Teachers of Mathematics (NCTM), 1980]. In 1982, the United Kingdom stated that the core of mathematics education is to cultivate the ability to solve mathematical problems, emphasizing that mathematics is meaningful only when it is applied to various situations [Department for Education and Science (DES), 1982]. Since then, many countries have addressed this issue. In 1989, Japan formally integrated the content of *Subject-Studying*, based on a mathematics class featuring problem-solving, in its newly revised *Curriculum Guidelines* (Fang et al., 1993). In 1990, Singapore's mathematics syllabus listed the development of students' mathematical problem-solving ability as the basic goal of the mathematics curriculum and, for the first time, proposed the pentagonal model of the mathematics curriculum framework, with mathematical problem-solving positioned as its core (Fan and Zhu, 2003). Currently, most countries regard improving students' problem-solving ability as an important goal of mathematics education, and problem-solving has become a popular topic in international mathematics curriculum and teaching research (Stacey, 2005; Manfreda, 2021).

In contrast, the People's Republic of China (1949–1957) was influenced by the educational climate of the time and adopted the Soviet mathematics teaching model, which emphasized abstraction, rigor, and application. It was not until the late 1970s that elementary and secondary mathematics syllabi noted that students should learn to apply mathematics knowledge to solve real-world problems. In modern China, the *Mathematics Curriculum Standards for Compulsory Education* (2011) consider problem-solving as the basic goal of school mathematics (Ministry of Education of the People's Republic of China, 2012), including the later *Ordinary High School Mathematics Curriculum Standards* (2002) and *General High School Mathematics Curriculum Standards* (2017). These curriculum standards emphasize learning to discover and pose problems from the perspective of mathematics, apply mathematics knowledge to solve practical problems, enhance application awareness, and improve practical ability (Ministry of Education of the People's Republic of China, 2003, 2020). As such, although China's research on problem-solving began relatively late, it has developed rapidly and is generally valued by the domestic mathematics education community.

Mathematical problems and problem-solving

American mathematician Halmos (1995) argues that the fundamental element of mathematics is the problem and answer, and the problem is the heart of mathematics. Thus, scholars from various countries have investigated what constitutes the problem. Polya (1965) states that a mathematical problem means to drive learners to find appropriate actions to achieve a visible—but not immediately accessible—goal. Similarly, several Japanese scholars believe that problem situations refer to those that do not yet have a direct solution, thus resulting in a cognitive challenge situation (Chen, 2007). Moreover, according to a renowned Chinese mathematics educator, a mathematics problem is a situation that a person wishes to comprehend, but for which standard solutions cannot be applied (Zhang, 1991). Therefore, mathematical problems refer to problems that learners can only solve through active exploration and thinking using existing mathematical concepts, theories, or methods.

However, consensus has also not yet been achieved regarding the concept of mathematical problem-solving. Perspectives can generally be classified into five categories: (1) mathematical problem-solving refers to facing new situations and issues in daily life and social practice that contradict subjective and objective needs and have no ready-made countermeasures, requiring psychological activity to seek solutions to problems that occur (Shao, 1983; Zhao, 2007); (2) mathematical problem-solving is considered to be the process of applying previously learned knowledge to new and unfamiliar situations (Tan, 2004); (3) mathematical problem-solving, as an important part of curriculum theory, is a type of teaching (Dai, 2012); (4) problem-solving is perceived as the purpose of mathematics teaching (Department for Education and Science (DES), 1982; Pasani, 2018); and (5) mathematical problem-solving is defined as the ability to apply mathematics to various situations (Mayer, 1992; Stacey, 2005). Despite the apparent inconsistency in the formation of problem-solving, the preceding explanations emphasize that mathematical problem-solving is not only an essential skill for all students, but also a process in which they use a variety of intellectual activities to find solutions to problems. In addition, it requires teachers to provide students with an environment and opportunities for discovery and innovation in the classroom. Furthermore, for students, mathematical problem-solving refers to the comprehensive and creative application of mathematical knowledge and methods to solve problems that are not pure exercises, including practical problems and problems derived from mathematics.

Psychological analysis of the process of mathematical problem-solving

Mathematical problem-solving is not only the core of mathematics education but also an important part of mathematics learning psychology. Therefore, research on the psychological mechanism of problem-solving is intriguing. However, various psychological theories maintain different interpretations of problem-solving, and there is no comprehensive view to date. The previous behaviorist theory considered problem-solving to be trial and error, while the Gestalt theory considers it to involve insight (Kilpatrick, 1978; Lumbelli, 2018). Actually, in the process of problem-solving, trial and error and insight are not mutually exclusive and often occur alternately. In addition, depending on its nature, a problem can be solved through trial and error or by relying on insight. Moreover, these behaviors are not entirely random but are organized behaviors that gradually search for information, establish connections between information, and adopt certain strategies. Cognitive psychology, a prevalent approach in Western psychology (Neisser, 1967), has largely promoted the theory of mathematics education. The information processing theory developed from cognitive psychology states that problem-solving is a process of finding, receiving, and processing information (Newell and Simon, 1972; Chien et al., 2016).

Based on psychological analyses of the process of solving mathematical problems, more researchers began to focus on the steps and procedures of problem-solving, especially observing the process of solving complex mathematical problems (Duncker, 1945; Hunt, 1968). The theory of information processing gradually aroused people's interest in the role of heuristic methods in the problem-solving process. The most influential was Polya's (1957) four-stage problem-solving process: understanding the problem, devising a plan, implementing the plan, and reviewing and testing. In addition, Mayer et al. (1991) also categorize the problem-solving process into three stages: paraphrasing, integration, and planning. In recent years, an increasing number of related studies on problem-solving steps and procedures, such as heuristic training (Wang, 2020), discovery learning (Hulukati et al., 2018), and other teaching procedures (Goulet-Lyle et al., 2019) have been applied to the teaching field.

Influencing factors of mathematical problem-solving

Factors that affect the solution of mathematical problems are elements that impact the problem-solving process. As problem-solving is a complex psychological process, it requires students to process the conditions, reorganize known concepts and theorems from the understanding of the basic relationship and characteristics of the problem, adjust the relationship between the basic elements in the problem, and explore and guess problem-solving strategies and methods. Based on the extant literature, many factors—such as knowledge, experience, motivation, confidence, thinking ability, and meta-cognition (Wang, 2017)—influence mathematical problem-solving. These factors can be classified into three categories: (1) the learner's individual internal factors, such as personal experience (personal characteristics of the problem solver), cognitive factors (intuition, imagination, abstraction, generalization, reasoning, analysis, and synthesis), meta-cognition, and non-intellectual factors, such as care, desire, motivation, interest, will, and belief (Ye and Zhang, 2004; Tan, 2009); (2) external factors related to the mathematical problem, such as complexity, familiarity, type, and context of the problem (OECD, 2013); and (3) teachers' problem-solving teaching, such as teaching self-efficacy of problem-solving and teaching methods for problem-solving (Schoenfeld, 1985).

Evaluation of mathematical problem solving ability at home and abroad

Although many scholars have conducted in-depth research on the steps, procedures, and open-ended questions of mathematical problem-solving, no unified and clear framework and standard for evaluating the ability of mathematical problem-solving exists. For instance, Mayer et al. (1991) designed 18 arithmetic problems using their original problem-solving procedures based on their previous psychological analysis of the mathematical problem-solving process, and the problems were used to compare the performance of English and Japanese fifth-grade students in mathematical problem-solving. However, mathematical problem-solving is not a single component, but an ability that involves simple calculations and reading comprehension as well as extensive reasoning skills (Kilpatrick, 1978). Various Chinese scholars believe that junior high school students' mathematical problem-solving abilities involve the four major ability elements of reading comprehension, mathematical modeling, problem-solving expression, and evaluation reflection (Bai, 2011). Thus, the mathematical problem-solving evaluation tools developed by scholars have gradually transitioned from simple to complex, and the problem form has changed from closed to open. As such, early mathematical problem-solving tests usually focused on the preparation of traditional arithmetic problems (Stinger et al., 1990). Later, various researchers began to design high-level cognitive diagnostic tools, such as the QUSAR Cognitive Assessment Instrument (QCAI), which highlights the important role of open-ended questions in mathematical problem-solving (Lane, 1993). On this basis, various studies have applied these open-ended problems related to cognitive diagnostic tools to specific problem-solving evaluations. Cai (1995) used the QCAI as a test tool in a comparative study on the mathematical problem-solving ability of sixth-grade students in China and the United States. Ding et al. (2009) also used the QUSAR QCAI in their study of the relationship between the elementary school mathematics classroom environment and students' problem-solving ability; they concluded that the dimensions of "happy" and "knowledge-related" in the classroom environment scale had a significant positive predictive effect on students' problem-solving ability and traditional test scores. All in all, few studies have examined the measurement and evaluation of mathematical problem-solving processes or comprehensively considered the relevant influencing factors of the mathematical problem-solving process. Evaluation design concepts are only incorporated in some representative mathematics curriculum standards and the evaluation framework of international comparison projects (Xu and Qi, 2018).

Analysis framework

On the whole, compared with foreign research on mathematical problem-solving, Chinese mathematics education pays special attention to the learning of mathematical problem-solving strategies and skills, such as in-depth analysis of external factors like the form, background and other elements of mathematical problems, but little attention is paid to the analysis of students' internal cognitive process of mathematical problem solving. On the other hand, although the domestic mathematics curriculum standards for middle schools also emphasize the role of non-intellectual factors such as mathematical affections in promoting learning, their attention is still obviously insufficient in the actual evaluation (Wang, 2000). In fact, research suggests that personal internal psychological factors, such as motivation, learning interest, and self-efficacy, are more significant in mathematical problem solving performance (Sun et al., 2016). Moreover, the impact of teaching factors on students' mathematical problem-solving performance also cannot be ignored (Schoenfeld, 1985). Therefore, to systematically evaluate the mathematical problem-solving ability, in addition to considering examining the structural elements of mathematical problem solving, the role of internal non-intellectual factors and teaching variables in the process of problem-solving must be valued.

In addition, the empirical investigation on the influencing factors of mathematical problem solving in the existing research is more just for the perspective of students or only considering the intervention of the teaching environment, so it is rare to combine these two together for comprehensive analysis. Therefore, at the technical level, multilevel models can be used to analyze the predictive effect of influencing factors at different levels (such as student level and school level) on the performance of middle school students' mathematical problem-solving ability, thus helping to find the key influencing factors in the school education environment, so as to promote the cultivation and improvement of students' mathematical problem-solving ability ultimately.

As such, on the basis of implementing academic requirements in the *Chinese Compulsory Education Mathematics Curriculum Standards*, this study designed test papers for evaluating students' mathematical problem-solving ability and questionnaires focusing on non-intellectual internal factors and teaching variables which affect students' mathematical problem-solving performance. It is hoped that this research can help the academic community to clearly clarify the current performance of middle school students' mathematical problem solving in mainland China, as well as the learning differences between student groups, schools and regions, and find the key factors that restrict the cultivation of students' mathematical problem solving ability, so as to provide targeted strategies for improving mathematical problem solving ability. The following research questions were posed:

1. What is the overall proficiency of middle school students' mathematical problem-solving ability in mainland China?

2. Do middle school students' mathematical problem-solving ability differ based upon gender and urban–rural environment?
3. What are the key factors that influence middle school students' mathematical problem-solving performance?

Materials and methods

Participants

This study utilized 2016 survey data provided by the *Regional Education Quality and Health Monitoring* team of the China Basic Education Quality Monitoring Collaborative Innovation Center. The *Regional Educational Quality and Health Monitoring* project is an important regional education investigation and evaluation program in China that is implemented annually. The program aims to conduct health monitoring on the quality of domestic mathematics education through standardized tests and questionnaires based on Chinese mathematics curriculum standards, and it proposes targeted improvements based on data analysis and evaluation. This study adopted a three-stage unequal probability sampling method. The first stage utilized the stratified probability proportionate to size (PPS) sampling method to extract counties (cities and districts). The second stage applied the hierarchical PPS method to extract schools. The third stage used random equidistant sampling to select students. Consequently, the sampling results provided a sample that was representative of the overall province and distribution of different groups, including cities, counties, towns, and rural areas. The study selected 42,968 ninth-grade students, who participated in the 2016 *Regional Education Quality and Health Monitoring* (used as the main data source), from 762 schools of Z province in East China. In addition, in terms of imputation, since the sample is large enough and the missing rate is only 0.75%, this study used the method of list-wise deletion to obtain 42,644 valid samples, including 22,302 boys (52.3%) and 20,342 girls (47.7%).

Instruments

This study was based on the *Regional Education Quality and Health Monitoring* project, which included middle school students' mathematical problem-solving test papers and student and teacher questionnaires on the factors influencing mathematical problem-solving.

Mathematical problem-solving test paper

The middle school mathematical problem-solving assessment of the *Regional Education Quality and Health Monitoring* project was guided by the *Mathematics Curriculum Standards for Compulsory Education* (2011), drawing on the experience of large-scale international mathematics assessment, this study designed the test paper for evaluating three dimensions (content, context and cognitive) of mathematical problem-solving process and questionnaires focusing on non-intellectual internal factors and teaching variables that affect students' problem-solving performance. In this study, mathematical problem solving was defined as an individual's ability to use cognitive processes to face and solve real, interdisciplinary problems. The mathematical problem-solving test paper consists of 10 items, including numbers and algebra, figures and geometry, and statistics and probability as the content dimensions to examine mathematical problem-solving ability; these items also involve three contexts: personal situation, social situation, and pure mathematical situation. Meanwhile, the cognitive processes involved in problem-solving are divided into three domains: knowing (four items), understanding (four items), and applying (two items), respectively. The test paper contains multiple-choice questions and subjective questions (including open-ended questions), with items including two to three questions. The difficulty of the test paper is about 0.70, the discrimination ranges between 0.40 and 0.80, about 76% of the items' discrimination is >0.40, and the internal consistency of the test paper is >0.9, which indicates that its reliability is good.

Questionnaires on factors influencing the performance of mathematical problem-solving

Based on the extant literature, a questionnaire was designed to identify factors affecting the performance of middle school students in solving mathematics problems. The significance of related influencing factors was investigated from the perspectives of students and teachers. Two questionnaires were compiled—one for students and another for teachers. The student questionnaire included four subscales: mathematics anxiety, mathematics interest, self-efficacy, and teacher–student relationship. The three subscales of mathematics anxiety, mathematics interest, and self-efficacy were adapted from the *Student Questionnaire* in PISA (translated into the Chinese version scales by the research team for application). Answers were given on a 5-point Likert scale ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). Higher scores indicated higher degrees of expression. Teacher–student relationship comprised a self-reported subscale rated on a 5-point Likert scale ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). The higher the score, the more harmonious the teacher–student relationship. In addition, to focus on the impact of teaching factors on students' mathematical problem-solving, the teaching self-efficacy of problem-solving and teaching methods for problem-solving subscales, rated on a 5-point Likert scale, were added to the teacher questionnaires for middle school mathematical problem-solving monitoring. Moreover, the internal consistency coefficients of the overall student questionnaire and teacher questionnaire were 0.91 and 0.89, respectively, and both types of questionnaires had good structural validity (CFI = 0.910, RMSEA = 0.054; CFI = 0.921, RMSEA = 0.070).

TABLE 1 The ratio of different proficiency levels of students' mathematical problem-solving ability.

Students' mathematical problem-solving proficiency in mainland China	Proficiency levels			
	A level	B level	C level	D level
Ratio	48%	35%	13%	4%

Data collection and test procedure

In order to collect test data quickly and efficiently, the China Basic Education Quality Monitoring Collaborative Innovation Center cooperated with the Department of Education in Z Province to jointly launch the project of *Regional Education Quality and Health Monitoring*. With the assistance of cities and counties (county-level cities and districts) in Z province, sampling tests were successfully organized and implemented in 11 cities and 104 districts and counties in Z Province in October 2016. Among them, 42,968 ninth grade students from 762 junior high schools participated in this test, while 42,644 of them finally filled out the *Student Questionnaire*. In addition, a total of 3,565 principals and vice-principals in charge of teaching of the participating schools filled out the *Principal Questionnaire*, 10,599 teachers answered the *Teacher Questionnaire*, and a total of 76,502 parents of students answered the *Parent Questionnaire*.

Meanwhile, for the test procedure, the mathematics project team has undergone a series of complete evaluation processes from the beginning of 2016 to November 2016, including framework testing and two-way specification table preparation, item collection and polishing, the first interviews with six participants, the round pre-tests of 30 participants, the second-round pre-tests of 300 participants, and the external reviews of domestic and foreign mathematics experts and assessment experts. Thus, implementing these procedures ultimately ensures the scientific and normative nature of the entire testing process (Qi et al., 2015).

Data processing

After going through the above test procedures, the project team first determined the scoring standards based on the standard answers of the test paper of mathematical problem-solving and the students' final formal participation in the test and then scored objectively according to the scoring standards. Next, the Rasch model from item response theory was used to analyze students' original scores to obtain their mathematical problem-solving ability value. Then, the ability value was converted into a standardized score (average 300, standard deviation 50), that is, the scale score that represents students' mathematical problem-solving performance. Simultaneously, the project team used the Angoff method[1] to calibrate the performance of students' mathematical problem-solving ability, and it divided the students into four levels (A, B, C, D) according to their mathematical problem-solving performance, where level C represents the benchmark of students' mathematical problem-solving. In contrast, the project also processed the original data from student and teacher questionnaires into a questionnaire database. In addition, this study first used the descriptive statistical analysis method to further describe the proficiency of students' mathematical problem-solving; then, it used the hierarchical linear model to analyze the inter-school differences in mathematical problem-solving performance and the predictive role of factors from different educational levels.

Results

Overall proficiency of students' mathematical problem-solving ability

To distinguish the characteristics of mathematical problems of different difficulty levels and the characteristics of students' mathematical problem-solving performance, this study divides the performance of all students' mathematical problem-solving ability into three proficiency levels from high to low, namely A level, B level, and C level, with each level representing the expected range of abilities for a different student group. Among them, students at the A level can comprehensively use basic knowledge in the process of mathematical problem-solving, master mathematical concepts, apply appropriate mathematical methods, or establish appropriate mathematical models to solve unfamiliar or open-ended problems. The group of students at the B level can understand the characteristics of mathematical concepts in the mathematical problem-solving process and apply appropriate mathematical methods or build simple mathematical models to solve relatively unfamiliar or unpracticed problems. Finally, students at the C level can only memorize and identify mathematical concepts in the mathematical problem-solving process and use conventional mathematical methods to solve familiar or practiced problems. In addition, below C level is defined as D level; the students at this level cannot analyze and interpret the answers nor evaluate and categorize problem-solving processes and methods. Table 1 shows that the mathematics problem-solving ability of middle school students in Z province in mainland China is relatively good; the majority of students' mathematical problem-solving skills are at a moderate to high level, and 48% of them have reached the A level, 35% the B level, and 13% the C level, with only 4% having located in the D level.

1 φ represents the effect size of the Chi-squared test.

TABLE 2 The compliance rate of middle school students' mathematical problem-solving performance.

The compliance rate of middle school students' mathematical problem-solving performance in mainland China (C level and above)			**Ratio**
Background variables	Gender	male	98%
		female	95%
	The only child situation	only children	97%
		non-only children	94%
	The leftover situation	leftover	95%
		non-leftover	96%
	Urban and rural background	Urban	98%
		County	97%
		Rural	95%

Background differences in the benchmark of students' mathematical problem-solving performance

As mentioned above, the C level represents the benchmark for students' mathematical problem-solving performance[2], which is the minimum requirement for middle school students' problem-solving skills in the *Mathematics Curriculum Standards for Compulsory Education* (2011). In other words, when a student's mathematical problem-solving proficiency reaches the C level and above, their problem-solving ability meets the curriculum standard's academic requirements. The survey found that 98% of boys' mathematics problem-solving ability reached the C level and above, 3 percentage points higher than girls, and the gender difference was significant ($p < 0.01$, $\varphi = 0.12$). Simultaneously, the proportion of only children (97%) reaching the C level and above was also significantly higher than that of non-only children (94%), and we observed a significant difference between the two ($p < 0.01$, $\varphi = 0.11$). In contrast, we found no significant difference between leftover students and non-leftover students in the compliance rate of the benchmark of mathematical problem-solving ability ($p > 0.05$, $\varphi = 0.06$), but the proportion of non-leftover students (96%) reaching the C level and above was slightly higher than that of leftover students (95%). In addition, we observed significant urban and rural differences in the performance of middle school students' mathematical problem-solving ability ($p < 0.01$, $\varphi = 0.21$), and 98% of urban students' mathematical problem-solving ability reached the C level and above, which was 1 and 3 percentage points higher than that of county students and rural students, respectively (see Table 2).

2 The Angoff method is one of the most commonly used in standard setting procedures and could be also used to determine the academic benchmark. Specifically, two or more split points were used in large-scale assessments to classify students' academic performance into multiple levels to determine classification criteria for different proficiency.

Students' mathematical problem-solving ability and influencing factor model setting

Our hierarchical linear model took students' mathematical problem-solving ability (the scale score) as the dependent variable; gender, leftover situation, only-child situation, mathematics interest, self-efficacy, teacher–student relationship, and mathematics anxiety as the student-level variables; and urban and rural backgrounds, teaching self-efficacy of problem-solving, and teaching methods for problem-solving as the school-or teacher-level variables.

Hierarchical linear model analysis

Due to the nested structure of the school-and student-level data, this study used the hierarchical linear model[3] to process them. Compared with the traditional regression method, this method can make full use of the data information of each level in the analysis of differences in mathematical problem-solving performance and decompose differences at each relevant level; thus, the source and size of the difference can be estimated more accurately. The analysis process involved two basic models: the null model and the random intercept model. The following analysis shows the regression equation model and the corresponding variance component analysis results after including the student-level variables and the school-level variables, respectively (see Table 3).

Model 0

$$Y_{ij} = \beta_{0j} + r_{ij} \quad \text{(Level 1)}$$

$$\beta_{0j} = \gamma_{00} + \mu_{0j} \quad \text{(Level 2)}$$

In Model 0, Y_{ij} is the mathematical problem-solving performance of i students in j school; β_{0j} is the average problem-solving performance of j school; r_{ij} is the random error of individual students, which indicates the difference between the i students in j school and the j school's average problem-solving performance; and γ_{00} is the overall average performance. μ_{0j} is the school's random error, which indicates the difference between the average problem-solving performance of the j school and the overall average performance.

Based on Model 0's student level, we establish Model 1, which adds variables denoting students' gender (male, female), only-child situation (yes, no), and leftover situation (yes, no),

3 In this study, the performance of the influencing factors is represented by the average value of multiple items that affect students' mathematical problem-solving ability.

TABLE 3 Students' mathematical problem-solving performance and influencing factors HLM analysis results.

	Variables	Model 0	Model 1	Model 2
Student level variables	Gender (Male–Female)		−6.54**	−6.12**
	The only child situation (Yes–No)		−5.58**	−4.79**
	The leftover situation (Yes–No)		2.98	0.37
	Math interest			10.06**
	Self-efficacy			15.34**
	Teacher-student relationship			3.66**
	Math anxiety			−14.08**
School level variables	Urban and rural background (Urban-County-Rural)		−18.11**	−14.91**
	Teaching self-efficacy of problem solving			1.51*
	Teaching methods to problem solving			4.63**
Variance estimation	Student level	4245.00	4236.40	3438.87
	School level	1670.21	1389.61	1013.48

The variance estimation results are nonstandard residual estimates, both of which are significant when p value is 0.001.

and school-level variables denoting urban versus rural background (urban, county, or rural), which study the influence of background variables on students' mathematical problem-solving.

Model 1

$$Y_{ij} = \beta_{0j} + \beta_{1j}(gender) + \beta_{2j}(only - child\ situation) + \beta_{3j}(leftover\ situation) + r_{ij};$$

$$\beta_{0j} = \gamma_{00} + \gamma_{01}(urban\ or\ rural\ background) + \mu_{0j};$$

$$\beta_{1j} = \gamma_{10}; \beta_{2j} = \gamma_{20}; \beta_{3j} = \gamma_{30}.$$

In Model 2, the following student-level variables are added: mathematics interest, self-efficacy, teacher–student relationship, and mathematics anxiety, which study the influence of individual non-intellectual variables on students' mathematical problem-solving. Meanwhile, teaching self-efficacy of problem-solving and teaching methods for problem-solving are added into the school level to study the influence of teaching-related variables on students' mathematical problem-solving.

Model 2

$$Y_{ij} = \beta_{0j} + \beta_{1j}(gender) + \beta_{2j}(only - child\ situation) + \beta_{3j}(leftover\ situation) + \beta_{4j}(mathematics\ interest) + \beta_{5j}(self - efficacy) + \beta_{6j}(teacher - student\ relationship) + \beta_{7j}(mathematics\ anxiety) + r_{ij};$$

$$\beta_{0j} = \gamma_{00} + \gamma_{01}(urban\ or\ rural\ background) + \gamma_{02}(teaching\ self - efficacy\ of\ problem - solving) + \gamma_{03}(teaching\ methods\ for\ problem - solving) + \mu_{0j};$$

$$\beta_{1j} = \gamma_{10}; \beta_{2j} = \gamma_{20}; \beta_{3j} = \gamma_{30}; \beta_{4j} = \gamma_{40}; \beta_{5j} = \gamma_{50}; \beta_{6j} = \gamma_{60}; \beta_{7j} = \gamma_{70}.$$

Model 0 represents the variance component analysis. By calculating the intraclass correlation coefficient (ICC), this study found that the ICC of the influential factors of ninth-grade students' mathematical problem-solving performance was about 28%, indicating that 28% of the problem-solving performance differences in middle school students in China's compulsory education come from inter-school differences. In other words, the model shows significant inter-group differences, and thus, it is necessary to use a hierarchical linear model for the analysis (Zhang et al., 2005).

After incorporating the background variables (Model 1), this study found that the student-level background variables (gender, the only-child situation, and the leftover situation) have little effect on students' mathematical problem-solving performance. Further observation of the regression coefficients of these student background variables showed that the mathematical problem-solving performance of boys was higher than that of girls, and the mathematical problem-solving performance of only children was higher than that of non-only children. By contrast, the urban or rural background, which belonged to school-level background variables, had a larger impact on the average school achievement (the absolute value of the regression coefficient was larger); specifically, the mathematical problem-solving performance of urban students was significantly higher than that of county and rural students. The above findings also corroborate the results of the previous Chi-squared test.

By observing Model 2, we found that the variance of the student-level residuals reduced more when mathematics interest, learning self-efficacy, teacher–student relationship, and mathematics anxiety were added into the student-level variables. Among these individual non-intelligence factors, the absolute value of the regression coefficient of self-efficacy was the largest, followed by mathematics anxiety and mathematics interest, and the smallest was teacher–student relationship. Simultaneously, the addition of two variables that belonged to school-level, namely teaching self-efficacy of problem-solving and teaching methods for problem-solving, greatly reduced the residuals at the school level. Although they were not as prominent as the effect of urban or rural background on mathematical problem-solving performance, teaching self-efficacy and teaching methods for problem-solving did have a significant impact on students' mathematical problem-solving, and teaching methods for problem-solving had a relatively larger positive effect.

Discussion

Overall performance of students' mathematical problem-solving ability

This study shows that in the four-level distribution of students' problem-solving ability performance, 96% of middle school students in Z province met the minimum requirements of the curriculum standard, and only 4% of students did not. This result is similar to the average level of problem-solving performance of students from OECD countries and regions that participated in the PISA 2012 test. For example, according to the students' problem-solving performance in the PISA 2012 survey report, the proportion of students in OECD countries and regions whose problem-solving ability was at level 1 and above was 91.8, and 8.2% of the students were still unable to reach the problem-solving benchmark. However, the difference is that in terms of problem-solving performance at the high level of difficulty, the performance of students from Z province in mainland China is more prominent, with the proportion of students at the A level and above as high as 48%, while the proportion of East Asian students at level 5 and above who participated in the PISA problem-solving test is lower than 20%, of which Hong Kong-China is 19.3%, and Chinese Taipei and Shanghai-China are both 18.3% (OECD, 2014). The above results may be due to Z province being located in East China, where China's education and economy are relatively developed. In fact, East China has always played an important role in the six administrative regions of mainland China, with its population and GDP accounting for more than 30% of the country. Moreover, in terms of basic education, the government of East China attaches importance to education investment, with well-equipped teachers and infrastructure, and balanced development among schools. Especially in mathematics education, mathematics teachers often have more unique teaching art and teaching strategies. For example, they often create a series of mathematical problem situations to stimulate students' cognition, so that students can understand the whole process of mathematical problem-solving (Zang, 2006). Thus, the students' overall mathematics academic level and mathematical problem-solving ability are relatively good, and students are especially able to successfully deal with mathematics problems of medium and high difficulty levels. Nevertheless, it cannot be overlooked that this study mainly relies on paper-and-pencil tests for the monitoring of mathematics problem-solving, and the East Asian middle school students participating in the PISA survey may have faced a more complex problem-solving test environment (the testing process, for instance, relied on computer technology); thus, their problem-solving ability performance may have been easily underestimated.

Differences in the benchmark of middle school students' mathematical problem-solving ability in mainland China

In this study, significant differences are observed with regard to gender and only-child situation in terms of mathematical problem-solving benchmark among students from different backgrounds, these differences are not practical. Many studies have also pointed out that no statistical difference exists in students' mathematical ability based on gender (Fennema and Sherman, 1976). However, from the perspective of cultural tradition, men in East Asia tend to have more educational expectations than women, which interferes with academic performance and mathematical ability (Zhu et al., 2018). On the other hand, retrospecting China's population policy changing, the sex ratio of the domestic population decreased from 107.56 in 1953 to 104.88 in 2021. Moreover, from the development trend, although it has been declining, the total number of men is still higher than that of women, and it is worth noting that the gender ratio of the population in East China is also higher than the national average (Yuan and Wu, 2022). Overall，Chinese boys are more likely than girls to perform at higher levels in problem-solving. As for family structure, according to the resource dilution theory, only children who receive family support are more likely to succeed in academic performance and mathematical ability improvement (Blake, 1981). In contrast, the differences in the performance of students' mathematical problem-solving abilities caused by different urban and rural backgrounds have more practical significance, this may be due to the significant, long-term urban–rural education gap in mainland China. In reality, although the country vigorously implements the policy of *Coordinated Development of Compulsory Education in Urban and Rural Areas*, objectively, the situation of urban education resources concentration and urban family education investment surge has not reversed, so the current situation of relatively weak education quality in districts, counties, towns and rural schools cannot be changed in the short term (Liu, 2006; Wei, 2018). Moreover, even in East China, where the development of basic education is relatively balanced, the educational differences between urban and rural areas are still significant. But the difference is that the gap between urban and rural education in East China is more about the quality of teachers than the hardware conditions such as infrastructure. For example, urban teachers can often get more high-level education and training opportunities (including the interpretation of mathematics curriculum standards), so they have a more accurate grasp of many teaching contents and more effective teaching methods (Zang, 2006). Therefore, on the whole, the performance of mathematical problem solving ability of urban students in Z Province is better than that of students in counties, towns and rural areas.

The predictive effect of student-level and school-level factors on mathematical problem-solving ability

On the whole, this study points out that 28% of the difference in mathematical problem-solving performance among middle school students in East China comes from inter-school variation, which shows that the imbalance of problem-solving between schools in compulsory education in mainland China still requires attention. According to the analysis results of the inter-school differences in PISA 2012, the percentage of the average variation in mathematical problem-solving performance among OECD members, accounting for school characteristics, is 38%. Simultaneously, the percentage of Shanghai samples who participated in the test on behalf of mainland China reaches 42%, while the mathematical problem-solving performance of students in countries such as Finland and Sweden is relatively balanced, with an average variation in problem-solving results across schools lower than 20% (OECD, 2014). The above results fully indicate that there is still space for improvement in the inter-school differences in the mathematical problem-solving of students in compulsory education in mainland China. As far as the current education situation in East China is concerned, the overall development level of basic education is relatively balanced, so the inter school differences in students' mathematical performance are not particularly prominent, which is mainly due to the positive measures taken in this region, such as paying attention to education layout planning and increasing support for weak schools (Zang, 2006). However, due to the long-term existence of urban–rural dual economic and social development structure, local weak rural schools have always been at a disadvantage in solving problems, and their school running quality and education investment are obviously insufficient (Liu, 2006). In addition, under the influence of social class differentiation, the average socioeconomic status of schools composed of students with different family socioeconomic statuses further exacerbates the Matthew effect of inter-school differences in mathematical problem-solving (Dumay and Dupriez, 2008).

In addition to the significant difference in the performance of middle school students' mathematical problem-solving ability caused by the gap between urban and rural backgrounds, the study also found that students' individual non-intelligence factors (e.g., mathematics interest, self-efficacy, teacher–student relationship, and mathematics anxiety) explained the difference in mathematical problem-solving more than students' background variables (e.g., gender, only-child situation, and leftover situation) did. The development of individual characteristics is always accompanied by the psychological maturity of students, which, when compared to individual background, may better predict problem-solving (Lu, 2011; Alibali et al., 2019). In addition, some studies have found that increasing middle school students' mathematics interest and self-efficacy can effectively improve their mathematical problem-solving, while excessive mathematics anxiety can hinder it (Xu and Qi, 2018). Similarly, this study demonstrated that mathematics interest, self-efficacy, and teacher–student relationship positively influenced students' problem-solving, while mathematics anxiety negatively affected it. This is because positive learning attitudes and persistence can promote mathematical thinking, while poor learning attitudes and habits can hinder mathematics learning and thinking (Huang, 2006). In view of this, in the future, mathematics teaching of secondary schools in various countries should pay more attention to the regulating role of non-intellectual factors like mathematical affections in the process of problem solving, such as actively creating mathematical problem situations to promote their interest in mathematics learning, increasing the opportunities for students about problem posing, and alleviating the anxiety of mathematical problem solving.

Furthermore, this study remarks that teaching factors are important for students' mathematical problem-solving ability; in particular, the teaching methods of mathematical problem-solving have played an important role in nurturing this ability because real teaching scenarios can provide students with step-by-step decomposition and reasoning analysis of the problem-solving process (Pasani, 2018). Therefore, for the cultivation of mathematical problem-solving ability in middle schools, the primary task of future mathematical classroom teaching is to improve the teaching strategy of problem-solving to activate students' mathematical cognition, such as appropriately transforming some open-ended problems with complex problem situations to help students gradually develop their mathematical thinking in the process of exploring the procedures of problem solving.

Limitations

This research has some limitations. First, although the *Regional Educational Quality and Health Monitoring* project adopted a relatively scientific PPS sampling method and included school students from different districts and counties and urban and rural backgrounds, such as administrative divisions, the main source was a sample of students from the upper levels of education and economy in East China. Therefore, the main findings of this study can provide appropriate reference for mathematics education in the developed regions of other countries, but at the same time, some conclusions still cannot be extended to the other regions of mainland China. For example, there may be differences between leftover and non-leftover students in China's underdeveloped provinces in mathematical problem-solving performance. In view of this, the follow-up research can further enrich the survey samples, such as expanding to the whole country. Second, from the type of math problem solving in test paper, the authors mainly use the two forms of multiple-choice questions and subjective questions commonly used in math tests in mainland China, which have less reference for the problem solving test questions in mathematics textbooks for secondary schools from other countries. Therefore, future research can consider from the perspective of textbook analysis to further enrich the form of math problem presentation in the current test paper, so as to facilitate subsequent international comparisons. Third, due to the limitation of the variables in the database, as this study did not choose SES and the school average SES as the optimal control variables in different levels but instead replaced them with the leftover situation and urban or rural background situation, the estimated results present deviations to a certain extent. Finally, limited by the volume of the questionnaire survey, the factors affecting the mathematical problem-solving ability selected in this study only involved students' background and internal non-intellectual factors, with less consideration of factors such as meta-cognition, including learning strategies, which may lead to limitations in the process of impact mechanism analysis. Thus, follow-up supplementary research could consider increasing the content of the student questionnaire on the influencing factors of mathematical problem-solving ability.

Conclusion

This study focused on the systematic monitoring and investigation of mathematical problem-solving ability of middle school students in the compulsory education stage in mainland China. It addressed the overall proficiency, background differences in the benchmark of ability, and the predictive effect of student-level and school-level factors on mathematical problem-solving performance, drawing meaningful conclusions.

First, the mathematics problem-solving ability of middle school students in Z province in mainland China is relatively good, and 96% of the students' mathematics problem-solving ability meets the basic academic requirements of the curriculum standards.

Second, in the difference analysis of the benchmark for middle school students' mathematical problem-solving ability performance, we found that the proportion of boys reaching the C level and above was significantly higher than that of girls, and the proportion of only children reaching the C level and above was also significantly higher than that of non-only children. In contrast, the proportion of non-leftover students reaching the C level and above was higher than that of leftover students, but no significant difference was observed between the two.

Finally, in terms of school-level variables, urban and rural backgrounds had a larger impact on mathematical problem-solving than teaching factors. Among the teaching factors, the teaching method of problem-solving had a relatively greater positive impact on problem-solving than the teaching self-efficacy. For student-level variables, the influence of individual non-intellectual factors on mathematical problem-solving was higher than that of student background variables, including a greater positive effect of self-efficacy and a higher negative effect of mathematics anxiety. Moreover, among the effects of student background on mathematical problem-solving, gender had the largest negative effect, followed by the effect of the only-child situation, while the positive impact of the leftover situation was not significant. In particular, only children and boys performed better.

Author's note

The samples used in this study were provided by the *Regional Educational Quality and Health Monitoring* project. The schools and education bureaus in the participating areas signed cooperative research agreements with the project team.

Data availability statement

The datasets presented in this article are not readily available because in view of the data confidentiality agreement, the data used in this study is only shared by members of the project team and cooperative institutes. Requests to access the datasets should be directed to qichuxia@126.com.

Ethics statement

The studies involving human participants were reviewed and approved by the Academic Committee of the Faculty of Education in Beijing Normal University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

ZX wrote this manuscript. CQ data provided and theoretical guidance. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The impact of students' mathematical attitudes on intentions, behavioral engagement, and mathematical performance in the China's context

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Referring to the theory of planned behavior (TPB), this study intends to investigate the impact of students' mathematical attitude determinants (i.e., attitude, subjective norms, and perceived behavioral control) on intentions, behavioral engagement, and mathematical performance. The data collected online in China's context and the research hypotheses are developed and then tested through structural equation modeling. It is found that attitude and subjective norms have effects, directly or indirectly, on intentions, behavioral engagement, and mathematical performance. In addition, the intentions have a significant effect on behavioral engagement, and behavioral engagement does likewise on mathematical performance. It has also been accepted that perceived behavioral control is not directly related to intentions but largely to behavior and indirectly to mathematical performance through behavior alone. In conclusion, this study's findings will contribute to the current literature on mathematical performance and will also inform the policymakers of the proposal on students' mathematics belief and attitude interventions as a means to improving students' mathematical performance.

KEYWORDS

attitude, subjective norms, perceived behavioral control, intentions, behavioral engagement, mathematical performance

Introduction

Mathematical performance refers to an individual's capacity to reason mathematically and to solve mathematical problems through formulation, employment, and interpretation of mathematics in the diverse contexts of the real world (OECD, 2018). The performance has received, as part of the core test contents of the Program for International Student Assessment (PISA), wide attention from the educational community (Cogan et al., 2019; Gjicali and Lipnevich, 2021). Mathematics is considered the key to promoting the development of the cognitive domain of students and is fundamental to students' future development and communication (Lavidas et al., 2022). Developing a strong foundation in early math skills is vital for children's later educational success and economic, health, and employment outcomes (Papadakis et al., 2016a). Children who enter school with strong mathematics skills have a greater likelihood of success in mathematics in kindergarten and later grades (Papadakis et al., 2021). Furthermore, mathematical performance can be a pivotal reference for student admission to higher institutions or well-paid career opportunities, as an indicator of competitiveness to meet the demands of economic globalization (Burrus and Moore, 2016). Longitudinal research indicates that low attainment in mathematics can have significant long-term consequences, affecting later school achievement, employment, criminality, mental health, and future earnings (Papadakis et al., 2016b, 2018). Particularly, in China, since the PISA 2012 Assessment and Analytical Framework in Shanghai came out among the top ones (OECD, 2013), math education has been drawing enormous attention and a research boom. The outcome also reproves that students from many other PISA member countries do not perform at expected levels in mathematical performance assessment (Fleischman et al., 2010). Hence, to predict students' mathematical performance, test factors can be essential for educational policy-making and practice.

From the literature available on mathematical performance, most studies focus on three dimensions, demographic (e.g., gender, socioeconomic status perspectives, and family resources) (Lopez et al., 2007; Thien, 2016; Kang and Cogan, 2020), cognitive (e.g., classroom context, teacher expectancy effects, school-level factors, and new technologies) (Papadakis et al., 2016a, 2018; Lazarevic and Orlic, 2018; Trusz, 2018; Kitsantas et al., 2021), or non-cognitive (e.g., anxiety, self-efficacy) (Niepel et al., 2018; Hiller et al., 2022). However, from the perspective of educational psychology, some studies relate non-cognitive constructs of beliefs and attitudes to mathematical performance, which has largely remained seldom explored (Burrus and Moore, 2016). Most previous studies concentrated on non-cognitive predictors of mathematical performance, mainly discussing student self-efficacy (Skaalvik et al., 2015; Kurniawati and Mahmudi, 2019), confidence in mathematics (Stankov et al., 2012, 2014), and motivational constructs (Garon-Carrier et al., 2016; Ker, 2017; Smart and Linder, 2018). Although some of the studies examined, longitudinally or cross-sectionally, the predictive value of mathematics beliefs and attitudes by referring to the theory of planned behavior (TPB) framework (Lipnevich et al., 2011; Niepel et al., 2018), there is still limited research relying on the predictive value of other non-cognitive factors such as attitudes and beliefs on mathematical performance. Recently, based on the PISA 2012 public-use data in the United States, Gjicali and Lipnevich (2021) investigated the impacts of students' mathematical attitudes on the intentions to study mathematics, behavioral engagement, and mathematical performance. In the extant literature, however, educational studies of the predictive roles of non-cognitive factors, such as attitudes and beliefs on mathematical performance, have not yet utilized China's data, still lacking the vast, complex, and diverse Chinese context.

Unlike prior studies treating behavioral engagement as a proxy for mathematical performance (Burrus and Moore, 2016; Niepel et al., 2018), this study modifies and extends the TPB framework applying one more component of mathematical performance and exploring specific academic behaviors as predictors of mathematical performance. This study investigates the correlation between students' mathematical attitudes and behavioral engagement. It also explores the mechanisms for a holistic understanding of the impact of students' mathematical attitudes on mathematical performance using the data collected in China. Specifically, we try to update all the mathematical attitude determinants (attitude, subjective norms, and perceived behavioral control) under the term "TPB-based students' mathematical attitudes."

This paper contributes four aspects. First, empirically it explores the effect of students' mathematical attitudes on mathematical performance by referring to the data collected in China. It also extends the studies on students' mathematical attitudes, in addition to previous ones mainly with the OCED member countries. Second, this paper, in the updated TPB structure, applies the modified model by introducing the mathematical performance, which is differentiated from behavioral engagement. Presuming behaviors as independent from mathematical performance, this study achieves a more accurate understanding of the behavior-literacy relevance in educational studies. Third, it examines, directly and indirectly, the effects of the attitude-specific determinants that are likely to influence intentions, behavioral engagement, and mathematical performance. Then, it goes on the probe into whether the intentions affect mathematics behavioral engagement and mathematical performance while trying to discover the correlation between mathematics behavioral engagement and mathematical performance. Fourth, the findings of this study may provide further support for their application in the domain of mathematics education. Also, for the sake of the policymakers and mathematics education researchers' reference to devise future mathematical attitude interventions, such extensive studies from the perspective of educational psychology would be of any implications.

The paper is structured as follows. Section "Theoretical background and hypothesis development" commences with the theoretical background and reviews the literature to conceive the research hypotheses and test them in this study. Section "Methodology" furnishes the sample and methodology to test these hypotheses. Section "Results" releases the empirical results. Section "Discussion" discusses the results and boils them down to findings. Finally, based on the findings, the conclusions are drawn in Section "Conclusion."

Theoretical background and hypothesis development

The theory of planned behavior

The TPB framework, which was coined by an American researcher Ajzen (1991), has its root in the theory of reasoned action (TRA). In light of TRA, subjective norms and behavioral attitudes are deemed as the driving factors that affect behavioral intention. With perceived behavioral control introduced as a factor, TRA was developed into a new, planned behavior theory research model, namely TPB. The model takes behavior intention as the directest influencing factor for behavioral engagement, while such intention is subject to attitude, subjective norms, and perceived behavioral control.

In the disciplines of psychology, management, and sociology, as well as the arenas of political participation and environmental protection, among others, researchers have used the TPB model to predict and explore the causal factors of different human behaviors in several approaches (Cooper et al., 2016), such as technological application (Rai et al., 2002), voluntary participation (Dawkins and Frass, 2005), examination of intention and entrepreneurial behavior (Kautonen et al., 2013), environmental conservation (Wauters et al., 2010), exercise of behaviors (Ickes and Sharma, 2012), and sleep patterning (Knowlden et al., 2012). At the same time, the TPB model has also been deployed to a possibly holistic extent within the field of studies on education. The model highlights the linkage of the instructional intentions of the prospective science teachers with their awareness and experience of science in their educational studies (Cooper et al., 2012). It is also used to predict teacher behavior, such as teacher development (Dunn et al., 2018), teacher entrepreneurship (Yang and Zhao, 2019), and technology-enabled learning (Watson and Rockinson-Szapkiw, 2021), all being intention-specific. In addition, the TPB model has been proposed to facilitate the understanding of student behavior and achievement (e.g., Cooper et al., 2016), such as student entrepreneurial intention (Wang et al., 2021), online interactive behaviors (Pan et al., 2021), mathematical performance (Lee and Stankov, 2018; Gjicali and Lipnevich, 2021), and mobile learning (Azizi and Khatony, 2019).

Through this study, we extend the TPB framework to explore the effects of students' mathematical attitudes on mathematical performance and deem specific behavioral engagement as a predictor of mathematical performance. In the TPB framework, the three students' mathematical attitude determinants are designated as attitude, subjective norms, and perceived behavioral control, to hypothesize and predict behavioral intention, behavioral engagement, and mathematical performance. The intention is deemed as a mediator among the students' mathematical attitude determinants and behavior. Furthermore, the TPB framework postulates that perceived behavioral control also has an indirect or mediated effect on behavioral engagement, through intention.

The theory of planned behavior-based students' mathematical attitudes and intention to pursue mathematics

The TPB-based students' mathematical attitudes comprise constructs, attitude, subjective norms, and perceived behavioral control, for the prediction of the intention (Ajzen, 1991). Attitude can be defined, by the TPB model, as the perceived evaluation of the consequences and behavioral characteristics, positive or negative (Azizi and Khatony, 2019). The subject norm implies an individual belief in the importance of people's thinking about the specific behavior and their act (Ajzen, 2005). Perceived behavior control indicates an individual perception level to perform a behavioral effort while measuring the individual control over behavior (Yeap et al., 2016).

Prior studies also suggest that the behavior of individuals may be strikingly affected by their confidence (Bandura et al., 1980). Through their experimental studies of student classroom attendance, Ajzen and Madden (1986) found that, after factoring in the mathematical attitude, determinants may act as a significant predictor of intention. A meta-analysis of the TPB efficacy also indicates that the attitudes, norms, and control may account for 39% of behavioral intention variants (Armitage and Conner, 2001). Recently, by sampling various US high schools, Niepel et al. (2018) identify the positive association of students' intention to succeed in mathematics with the aforesaid mathematical attitude determinants.

Therefore, we intend to test the following hypotheses:

> H1: The significant effect of students' attitudes on their intentions to pursue mathematics.

> H2: The remarkable effect of subjective norms on the same intentions.

> H3: The noticeable effect of students' perceived behavioral control on identical intention.

Students' mathematical attitudes, intentions, behavioral engagement, and mathematics performance

An intention implies to be one's willingness to exert a certain behavior (Gjicali and Lipnevich, 2021). Ajzen (2005), in his studies, proved a significant attribution of the factor of volitional behavior to an individual's intention of engagement in that behavior. Furthermore, based on their survey of some 15-year-old students Hagger et al. (2015), documented that, while intentions of mathematics learning predict that for the grades and homework behavior in the discipline, perceived behavioral control directly did the same to the outcomes of both factors. There is evidence suggesting that TPB-based mathematical beliefs and attitudes may herald mathematical performance and achievement (Simzar et al., 2015). Other prior studies have also demonstrated the conceptional relevance of perceived behavioral control to self-efficacy beliefs (Bandura, 1977). Furthermore, based on the survey of the Grade X junior high school students, Simzar et al. (2015) see that mathematics self-efficacy predicts mathematics achievement.

Some studies indicate that a great deal of academic behaviors constitutes some behavioral factors contributing to academic achievements (Gjicali and Lipnevich, 2021). By sampling 34 countries that ever participated in the PISA 2012, Fung et al. (2018) concluded that student participants in more varied mathematics behavior promise higher levels of mathematics achievement. However, a survey of 14,000-plus student participants in the OECD's PISA, Australia, revealed that the TPB-based students' mathematical attitudes turn out to be poor predictors of mathematical intentions and mathematical behavior (Skrzypiec and Lai, 2017). Moreover, the PISA 2012 evidence demonstrates that students' attitudinal beliefs (e.g., dispositional, normative, and control beliefs) about mathematics (Areepattamannil et al., 2016), perceived behavioral control toward mathematics (Karakolidis et al., 2016), and high subjective norms (Areepattamannil et al., 2015) are, unexceptionally, all associated with mathematics behaviors and mathematical performance.

One recent study differentiated students' behaviors as an independent factor from mathematical performance, treating behavioral engagement as a predictor of mathematics achievement (Gjicali and Lipnevich, 2021). In the PISA, mathematical performance is gauged with test questions for mathematics literacy, access to mathematical reasoning and tools in personal and professional contexts (OECD, 2018).

Therefore, we intend to test the following hypotheses:

> H4: The direct effect of students' perceived behavioral control over mathematics behavioral engagement.

> H5: The significant effect of their intention to pursue mathematics on mathematics behavioral engagement.

> H6: The significant effect of their mathematics behavioral engagement on mathematics performance.

> H7: The indirect effect of their perceived behavioral control over mathematics on mathematical performance through behavioral engagement.

> H8: The indirect effect of their mathematical attitudes, subjective norms, and perceived behavioral control, respectively, on mathematical performance through intention and behavioral engagement.

In conclusion, to string these relationships up, we have developed a conceptual model (refer to **Figure 1**).

Methodology

Sample and data collection

In this study, we select Grade 9 junior high school students as the study subjects. Data were collected using online tests and online questionnaires. All participants voluntarily agreed to take part in the study. As they were all minors, their guardians approved their participation in the study by signing the research information letter. All students who participated in the test entered the computer classroom and utilized the test platform under the guidance of the teacher. Before the actual research, a pre-study was carried out with some Grade 9 high schoolers in Yunnan Province of China, with the questions revised repeatedly into the formal questionnaire. The survey proceeded from 5 January 2022 to 28 February 2022, the sample being used a random sampling method and mainly taken from Yunnan Province, Guizhou Province, Guangxi Province, Guangdong Province, and Shandong Province of China. A total of 405 questionnaires were returned, and 326 were deemed valid with a return rate of 80.49%, exclusive of the incomplete and invalid ones. The assessed subjects average 15.81 years of age, 53.4% of whom are boys and 46.6% girls, at a male-to-female ratio of 1:0.87. After the sampling and data collection, the research data are processed and analyzed using SPSS26.0 and AMOS24.0.

Variables and measurement

To ensure the reliability and validity of the measurement instrument, this study intends to apply, as far as possible, well-established scales in the existing literature, with appropriate modifications for the purpose of the measurement questions. Ratings of attitude, subjective norms, perceived behavioral control, and behavioral engagement are based on a 4-point Likert scale, by which the variables are scored 1 up to 4 points (1 = strongly agree, 2 = agree, 3 = disagree, and 4 = strongly

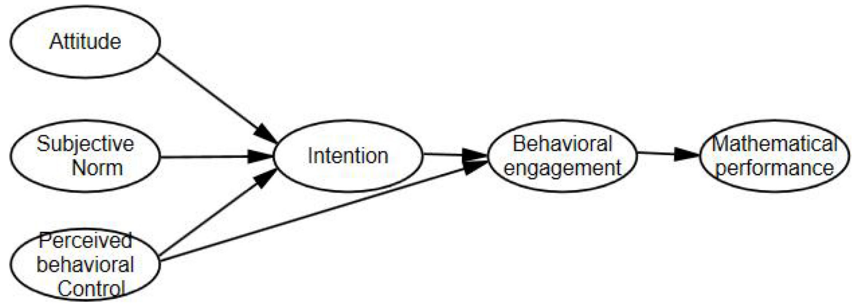

FIGURE 1
Conceptual framework.

disagree). Specifically, the five items of the intention factor are measured, by forced choice, adapted from OECD (2014) and Gjicali and Lipnevich (2021); six items of the subjective norms factor are scaled, according to OECD (2014); six items of the perceived behavioral control factor are included, with reference to Gjicali and Lipnevich (2021); and eight items of the behavioral engagement are examined in Fung et al. (2018). In addition, the high school student subjects' average scores on the mid- and final-semester exams are referred to as mathematical performance.

Results

Tests for reliability and validity

For the sake of assessment of the reliability of the variables on the measurements, we adopt Cronbach's alpha to test for their internal consistency, and by confirmatory factor analysis, we intend to demonstrate convergent validity by adopting SPSS 26.0. As shown in **Table 1**, Cronbach's alpha coefficient for each measuring dimension is greater than 0.8, suggesting good reliability for the aforesaid sampling data.

To assess the validity of the variables in the measurements, this study explored convergent validity and discriminative validity. In particular, convergent validity is determined by composite reliability (CR) and average variance extracted (AVE). Also, if the square root of the AVE of a variable is greater than the correlation coefficient of that variable with the other ones, the differential validity can be assessed as good. As shown in **Table 1**, the CR and AVE values for this study are greater than the standard values of 0.8 and 0.5, respectively, indicating good convergent validity of the scale (Nunnally, 1978). In addition, coefficients greater than 0.6 for each dimensional measure may effectively reflect the potential traits of their corresponding dimensions. In **Table 2**, the AVE open root value for each latent variable is greater than the correlation coefficient between that latent variable and the other latent variables. Therefore, the measurement model is of differential validity (Fornell and Larcker, 1981). To sum up, the findings of this study show that the efficiency and integrity of each build are satisfactory.

Model fit test

Model fit is the degree of consistency between the theoretical model and the sample model. AMOS 24.0 is used to test the model's goodness of fit. The goodness-of-fit index (GFI), adjusted goodness-of-fit index (AGFI), relative fit index (TLI), and comparative fit index (CFI) are all greater than 0.9; the closer to 1.0 suggests the better goodness of fit between the data and the model, and the greater than 0.8, an acceptable model. Provided that the variability index RMSEA is less than 0.080, the model is assessed as a good fit (Wu, 2000).

The test results are shown in **Table 3**, $\chi^2/df = 1.484$, GFI = 0.903, AGFI = 0.885, TLI = 0.962, CFI = 0.965, and RMSEA = 0.039. Therefore, the sample model has good goodness of fit.

Hypothesis testing

The results of the path relationship are illustrated in **Table 4**. As predicted, the attitudes are related positively to student intentions to pursue mathematics ($\beta = 0.203$, $SE = 0.071$, $p = 0.01$), and so we interpret the result as supportive of H1. The subjective norms significantly influence their intentions to pursue mathematics ($\beta = 0.293$, $SE = 0.117$, $p < 0.01$), and thus, the result is considered supportive of H2. Similarly, the perceived behavioral control is related positively to behavioral engagement ($\beta = 0.309$, $SE = 0.075$, $p < 0.01$), and therefore, the result is deemed supportive of H4. However, the perceived behavioral control does not significantly affect their intention to pursue mathematics ($\beta = 0.084$, $SE = 0.070$, $p = 0.226$), and consequently, the result is found to be non-supportive of H3. In addition, the intention to

TABLE 1 Reliability and convergent validity.

Constructs	Test items	Factor loading	Cronbach' α	CR	AVE
Attitude	Trying hard at school will help me secure a good job.	0.759	0.827	0.833	0.555
	Trying hard at school will help me be admitted to a good college.	0.807			
	I enjoy being rated high grades.	0.685			
	Trying hard at school matters.	0.724			
Subjective Norms	Most of my friends do well in math.	0.746	0.867	0.859	0.505
	Most of my friends work hard at math.	0.746			
	My friends encourage me to take math tests.	0.648			
	My parents believe that it's important for me to study math.	0.682			
	My parents believe that math is important for my career.	0.718			
	My parents like math.	0.717			
Perceived behavioral control	I can succeed in math learning with enough efforts.	0.820	0.907	0.910	0.629
	Doing well in math is completely up to me.	0.771			
	If I wanted to, I can perform well in math learning.	0.805			
	My family demands me to work out math problems.	0.791			
	I have different math teachers.	0.761			
	I perform poorly in math learning regardless of efforts.	0.808			
Intention	I intend to take additional math courses after school.	0.790	0.842	0.872	0.576
	I plan to take a major in college that requires math skills.	0.715			
	I am willing to study harder in math classes than the course requires.	0.731			
	I plan on taking as many math classes as I can during my schooling.	0.757			
	I plan to pursue a career that involves much math learning.	0.799			
Behavioral engagement	I finish my assignment in time for math class,	0.829	0.941	0.936	0.646
	I work hard at my math homework.	0.814			
	I am preparing for my math exams.	0.753			
	I keep studying until I understand math material.	0.814			
	I have the motivation to attend the math class.	0.820			
	I listen to the teacher attentively in math class.	0.734			
	I avoid distractions when I am studying math.	0.788			
	I keep my math work well-structured.	0.871			

TABLE 2 Validity of potential variables.

Constructs	Mean	Std. D	Attitude	Subjective norms	Perceived behavioral control	Intention	Behavioral engagement
Attitude	3.273	0.966	**0.745**				
Subjective norms	3.456	0.822	0.466**	**0.711**			
Perceived behavioral control	3.648	0.847	0.324**	0.432**	**0.793**		
Intention	3.255	0.850	0.315**	0.370**	0.263**	**0.759**	
Behavioral engagement	3.329	0.999	0.475**	0.475**	0.336**	0.252**	**0.804**

*The diagonal bold text stands for the open root value of the AVE. **$P < 0.01$.

TABLE 3 Fit indices of measurement and structural model.

Fit index	χ^2/df	GFI	AGFI	TLI	CFI	RMSEA
Reference value	<3	>0.9	>0.8	>0.9	>0.9	<0.08
Examined value	1.484	0.903	0.885	0.901	0.962	0.039

TABLE 4 Test results of path relationship.

Hypothesized relationship	B	*SE*	*t*-value	*P*-value	Supported?
Attitude– > Intention	0.203	0.071	2.593	0.01	Yes
Subjective norms– > Intention	0.293	0.117	3.431	<0.001	Yes
Perceived behavioral control– > Intention	0.084	0.07	1.211	0.226	No
Intention– > Behavioral engagement	0.211	0.076	3.431	<0.001	Yes
Perceived behavioral control– > Behavioral engagement	0.309	0.075	5.124	<0.001	Yes
Behavioral engagement– > Mathematical performance	0.348	0.747	6.422	<0.001	Yes

TABLE 5 Test results of mediation analysis.

Hypothesized relationship	Estimate	95% CI	*P*-value	Supported?
Perceived behavioral control– > Behavioral engagement– > mathematical performance	0.108	[0.065, 0.167]	0	Yes
Attitude– > Intention– > Behavioral engagement– > Mathematical performance	0.015	[0.003, 0.041]	0.011	Yes
Subjective norms– > Intention– > Behavioral engagement– > Mathematical performance	0.022	[0.006, 0.051]	0.04	Yes
Perceived behavioral control– > Intention– > Behavioral Engagement– > Mathematical performance	0.006	[−0.004, 0.023]	0.178	No

pursue mathematics significantly affects mathematics behavioral engagement ($\beta = 0.211$, $SE = 0.076$, $p < 0.01$), and accordingly, the result is seen as supportive of H5. The mathematics behavioral engagement is related positively to mathematical performance ($\beta = 0.348$, $SE = 0.747$, $p < 0.01$), which hence leads to the acceptance of H6.

The results of the mediation analysis are specified in **Table 5**. We find that perceived behavioral control has an indirect effect on mathematical performance through behavioral engagement ($p = 0 < 0.01$, 95% CI [0.065, 0.167]), and thus, the result indicates that H7 applies. In addition, the attitudes have an indirect effect on mathematical performance through intention and behavioral engagement ($p < 0.05$, 95% CI [0.003, 0.041]). Similarly, subjective norms have an indirect effect on mathematical performance through intention and behavioral engagement ($p < 0.05$, 95% CI [0.006, 0.051]). However, perceived behavioral control has indirect effects on mathematical performance through intention and behavioral engagement ($p = 0.178$, 95%CI [−0.004, 0.023]). Therefore, the result can be inferred as partially supportive of H8.

After the above path analysis and hypothesis testing, the specific path relationships between students' mathematical attitudes, intentions, behavioral engagement, and mathematical performance in the research model are shown in **Figure 2**.

Discussion

The results of our study show that students' attitude and subjective norms affect their intentions to pursue mathematics positively to a great extent (H1 and H2). Similar to the results Lipnevich et al. (2016), hypothesize that the students' attitudes toward mathematics have the strongest correlation to intentions. Hagger et al. (2015) also find that attitude and subjective norms predict intention. Contrary to one of the aforesaid hypotheses, we do not find perceived behavioral control's significant connection to their intentions (H3). As for the perceived behavioral control, to some extent, similar to the findings of Gjicali and Lipnevich (2021), is found indirectly related to intentions. The students' sense of competency over accomplishing a particular action or achieving the goal does not directly affect the students' intention. However, there are conflicting results, from considerable studies. For example, Niepel et al. (2018) argue that the student's intention to pursue mathematics is determined by attitudes toward the behavior, subjective norms, and perceived behavioral control, which can be interrelated and might account for the different results of longitudinal designs in data collection.

Perceived behavioral control is found to affect behavioral engagement (H4). Similar studies have been conducted by Areepattamannil et al. (2016), who adopt the Qatari sample of the PISA 2012, and they also find that students' perceived behavioral control about mathematics is associated with mathematics behaviors. In addition, behavioral engagement as a mediator between perceived behavioral control and mathematical performance is proven by this study (H7). This is consistent with the study of You et al. (2011), who together demonstrate that perceived behavioral control has an indirect effect on mathematical performance through behavioral engagement. It is noteworthy that perceived behavioral control is not directly related to intentions, but largely, to behavior and indirectly related to mathematical performance through behavior alone. The fact is that, regarding the indirect effect of perceived behavioral control on behavior, intentions are not a particularly useful factor in mediating that relation (Gjicali and Lipnevich, 2021).

The results in this study show that students' intentions to pursue mathematics affect behavioral engagement (H5),

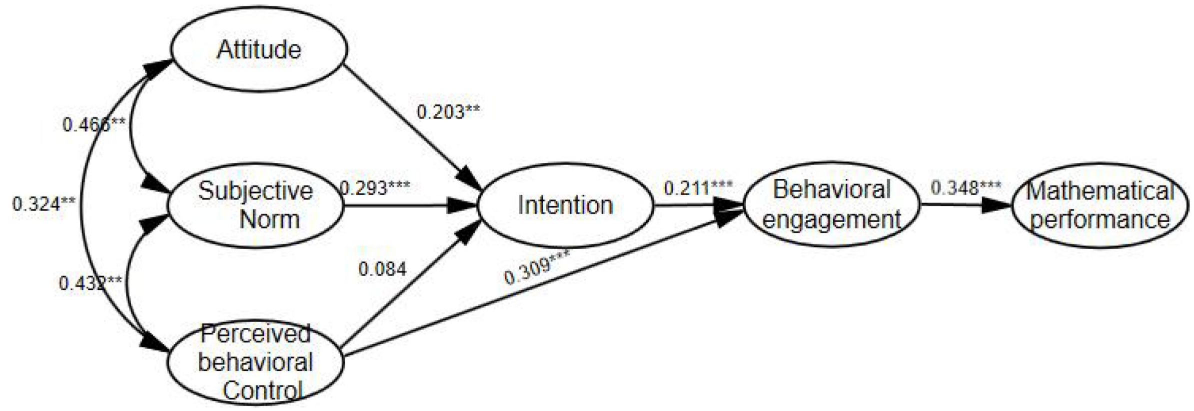

FIGURE 2
Path relationships.

and mathematics behavioral engagement significantly affects mathematical performance (H6). The student's intentions to pursue mathematics-relevant coursework or careers after high school are essential for predicting their behavioral engagement (e.g., day-to-day work ethic on mathematics homework, exam preparations, and attentiveness in class) (Gjicali and Lipnevich, 2021). Fung et al. (2018) also found a positive relationship between behavioral engagement and mathematical performance. In accordance with the literature related, Robinson and Mueller (2014) found that the components of students' engagement, affective, behavioral, or cognitive, are individually related to their mathematics achievement (2014). Additionally, some studies (Burrus and Moore, 2016; Niepel et al., 2018) apply the TPB model to interpret the variability in mathematics achievement in conflating academic behaviors and achievements.

Analyses of the mediating effects of intentions indicate that the students' mathematical attitudes and subjective norms are found to have an indirect impact on mathematical performance through intention and behavioral engagement, whose outcome partially supports H8. Fostering students' attitudes toward mathematics are believed to have a positive effect on academic intentions, behaviors, and achievements. The finding that subjective norms are related to the academic outcomes of interest in this study (intentions, behavior, and subsequent mathematical performance) is also found consistent with Burrus and Moore (2016) and Niepel et al. (2018). Conversely, Gjicali and Lipnevich (2021) observe that subjective norms have negative effects on outcomes, direct or indirect. Also, while we adapt subjective norms from the PISA index, Gjicali and Lipnevich practice social norms from the broader psychological literature on attitudes toward sociomathematical norms. One more consideration could be the economic and cultural factors (China vs. United States) with different results.

Conclusion

The main purpose of this study is to focus on analyses of both the direct and indirect effects of the TPB-based students' mathematical attitude determinants on intentions, behavioral engagement, and mathematical performance. In this study, we use an extended TPB framework with a sample of 326 junior high school students in a Chinese context, and the research hypotheses are developed and tested through structural equation modeling. The conclusions can be summarized as follows: First, the attitude determinants are of direct and indirect effects on intentions, behavioral engagement, and mathematical performance. Second, perceived behavioral control is not directly related to intentions but rather, largely related to behavior and indirectly related to mathematical performance through behavior alone. Third, the students' intentions to pursue mathematics are found to affect behavioral engagement, and the mathematics behavioral engagement significantly affects mathematical performance.

The theoretical contribution of the study includes the following: First, the TPB is a viable theoretical framework for predicting high school students' mathematical performance in China, and the theory is applicable to relevant educational research. Second, it extends prior literature by quantifying the relationship between mathematical attitude determinants and mathematical performance in the context of China. Third, the current study takes specific academic behaviors as predictors of mathematical performance. The literature review, as a whole, shows that previous studies have predicted educational outcomes and have treated behavioral engagement as a proxy for mathematical performance. Finally, this study can be a reference for future research to further explore mathematical attitudes and their impact on mathematical performance in other parts of the world.

The findings of the current study provide several supports for their application in the fields of educational and psychological research. Policymakers and mathematics education researchers should focus on how to develop students' confidence in the mathematical attitude determinants to achieve a higher level of mathematical performance, such as mathematics value promotion, social pressure reduction, self-efficacy increase, and explicit instruction of effective mathematics-related behaviors. In addition, the teachers need to be trained in specific instructional strategies to enhance students' positive attitudes and self-efficacy beliefs in mathematics. They are also expected to draw students' attention to their growth, encourage their students to try harder, and praise the students on any progress in specific mathematical skills. Finally, policymakers can rely on extensive research in the fields of social and educational psychology to design future mathematics beliefs and attitudes interventions.

Nonetheless, this study still has some limitations. First, owing to time constraints and the sampler's unavailability, the sample size of this study was only confined to some provinces, which could have been extended across the country, with a much larger size of samples and rigorously verified error-free data. Second, sample data from different countries or regions should be included and compared with China's data, and it should be extended to students in the other grades of high school as well. Third, the subjectivity of measurement indicators is hardly avoidable. Although its design may reduce bias and errors to a certain extent, this study adopted domestic and international scales and conducted a pilot study before the formal investigation to minimize the impact of subjective errors. However, such errors may still inevitably exist, which will be further minimized in future studies through in-depth interviews based on the grounded theory and qualitative survey. In addition, there are quite a few influencing factors (e.g., home education, teacher level, social, cultural, and economic disadvantage) that might affect mathematical performance. This study just investigated some factors, still losing sight of many others, which can be further studied in later studies by introducing possibly sufficient variables from more diverse perspectives.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This study involving human participants were reviewed and approved by the Scientific Ethics Committee of the Academic Committee of the School of Foreign Languages, West Yunnan University. All parents/guardians signed a statement of consent authorizing the participation of their children.

Author contributions

LW, FP, and NS conceived the idea of the study and designed the study. LW and FP were conducted the data analyses, interpreted the results, and drafted the manuscript. NS provided feedback and co-wrote the final submission. All authors contributed to the manuscript revision.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The intervention of Brain Gym in the mathematical abilities of high-school students: A pilot study

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Introduction: The learning process of Mathematics is a challenge in Latin America; therefore, it is of vital importance to conduct actions that improve the performance in this science.

Methods: This article is reporting on quasi-experimental research, where, through the use of Brain Gym, the objective is to improve: the definition of rational numbers, problem-solving ability, mathematical order relationships, and equivalent fractions. We worked with 67 students between 12 and 14years old, organized into an experimental group (n=35) and a control group (no participation group; n=32).

Results: We made pre and post-test measurements and found that the control group students improved in their problem-solving ability $F(1,65)=8.76$, $p=0.04$, $\eta^2=0.12$ and equivalent fractions $F(1,65)=4.54$, $p=0.03$, $\eta^2=0.06$.

Discussion: In conclusion, the importance of applying innovative processes to improve the teaching and learning of Mathematics can be affirmed. It is important to note that both the control and experimental groups improved their learning, however, the experimental group did so to a greater extent than the students in the control group, who received a traditional educational process, and they did learn, but not at the level of the experimental group.

KEYWORDS

Brain Gym, Mathematics, problem-solving, cognitive skills, fractions

Introduction

Mathematics is a science that strengthens the progress and scientific advancement of society. Its study has become necessary and essential for the improvement of people's life quality, organizations, and the economic development of countries for centuries (Chavarría-Arroyo and Albanese, 2021). In the educational context, it is important to relate it to social and cultural life. In addition, it contributes to the curiosity and creativity of students to solve environmental problems with critical, reflective, analytical, systematic, numerical, and logical thinking (Ministry of Education [MINEDUC], 2019).

As part of the knowledge of Mathematics, the understanding of the definition and elements of rational numbers helps to strengthen the thought units that give meaning to those situations where there is a division of the unit of the numerator and denominator. The order relationship strengthens the analysis of the numerical value to establish a comparison between greater, lesser, or equal several rational numbers. By recognizing and constructing equivalent fractions with the ability to calculate through amplification and simplification, it is possible to obtain another fraction with the same value (Ministry of Education [MINEDUC], 2019).

Problem-solving develops critical, reflective, and metacognitive thinking. This mathematical ability starts from reading comprehension, planning of the resolution process, the execution of the planning, in which the mathematical calculations are executed, and finishes with the verification of the answer. This mathematical knowledge is essential to develop life learning skills (Torregrosa et al., 2020).

In spite of the great importance of learning Mathematics, its learning and teaching process has difficulties that generate a negative impact on cognitive skills, critical thinking, and calculation, and at the same time, make students avoid wanting to solve difficult mathematical problems (Adiastuty, 2021). In recent decades, there has been research that has detected that the educational model fails to achieve the learning skills of Mathematics. In addition, it is labeled as a difficult subject that is scary and boring. As result, it has become a concern for teachers, educators, and researchers worldwide (García, 2013; Cai and Mok, 2017).

According to results of evaluations in Mathematics worldwide, it has been reported that countries such as Singapore, China, and the United States lead the learning of this science (González-Mayorga et al., 2022). In Latin America, where this research is done, it has been found that countries such as Uruguay and Chile lead the performance in Mathematics, while, ranking lower, we have countries such as Ecuador, with a lower performance in calculation skills (Instituto Nacional de Evaluación Educativa [INEVAL], 2018; Organization for Economic Co-operation and Development, 2019).

Similarly, previous studies reveal that the student's lack of cognitive skills in problem-solving, development of critical thinking, and calculation exercises can cause professional failure, which motivates a percentage of teachers to be interested in developing innovative didactic learning strategies that are significant and useful. And at the same time, provide solutions to cognitive difficulties, especially in the area of Mathematics. They also improve the repercussions that could be generated in society (Mulyanto, 2018; González and Rodríguez, 2022).

Within these innovative activities to contribute to the solution of the problem of the teaching and learning of Mathematics, the application of Brain Gym arises as a new experience that, through the brain-movement-body connection, accelerates the learning of it. Significantly, supporting the lack of attention, memory, comprehension, and organization problems. In addition, research shows that Brain Gym reduces the stress that can be generated by learning the different contents of Mathematics slowly or difficultly. Therefore providing an active strategy that strengthens the student's cognitive capacity (Marpaung, 2017).

Brain Gym is a set of movements whose objective is to connect the body and the mind, stimulate the use of the cerebral hemispheres through physical and mental strategies, and also improve and strengthen cognitive functions to learn. It is part of Kinesiology and it's the result of the research of Applied Neuroscience that studies the movements of the body and its relationship with brain function. It also allows stimulating and activating the cognitive process of an individual (Hoffman, 2009; Spaulding et al., 2010; Ferré, 2016; Marpaung, 2017; Ministry of Education [MINEDUC], 2020).

The Brain Gym program is applied through the PACE process, whose acronym stands for positive, active, clear, and energetic. It corresponds to the sequence of the four essential qualities that prepare a student for integrated learning in the brain. The chosen exercises are used in a basic way to maintain a balance in daily life, respecting rhythm and times. The qualities of being energetic, clear, active, and positive are related to the three types of movements that come from the central line, dividing the body into two equal parts: left–right, anterior–posterior, and up-down. These movements are based on the dimensions that become the pillar base to the understanding of how learning works, while applying the exercises of Brain Gym (Brain Gym International, 2018).

In the Brain Gym method, it is assumed that the brain can be trained and become more efficient through motor exercises, practically being like a muscle that needs to be exercised to perform better (Groose, 2013). With the exercises of this method, a better connection between the left and right hemispheres is promoted, thus achieving a neuronal unlocking and favoring the learning process and neuronal synapsis (Jalilinasab et al., 2021).

Another element that favors at the cerebral level has to do with the activation of tone and wakefulness that human beings need to carry out a cognitive activity. In this case, the exercises increase the alert state of the subject, which will have a positive impact on functions such as attention, since by finding a better cortical tone, the subject will be able to concentrate more and improve their information processing (Ramos-Galarza et al., 2021).

The key to Brain Gym brain stimulation is based on how brain connections are activated with motor exercises and through the visual and auditory stimulation proposed by this method. What it would generate in the student's mind is an optimal balanced state for their learning to take place, as is the case of this research, in the mathematics area (Spaulding et al., 2010).

The use of Brain Gym helps the human being in various areas in which he develops, such as education, sociability and health, among others. Investigations such as that of Arbianingsih et al. (2021) report the reduction of anxiety in hospitalized children of preschool and school-age, after applying Brain Gym exercises. According to Anggraini and Dewi (2022), concentration increases significantly, improving the teaching and learning process with the use of Brain Gym. At the level of academic performance of university students, according to Ramírez et al. (2021), the influence of Brain Gym exercises applied as a didactic strategy in Physical Education, reported that this type of intervention increases the performance in Mathematics and Communication. Other studies have reported the positive effects of applying Brain Gym in various populations to treat mental health problems and improve life quality (Surita et al., 2021).

Various studies have highlighted the benefit of the Brain Gym method, for example, it has been reported that this type of stimulation benefits motor and social skills (Jalilinasab et al., 2021), quality of life (Andi et al., 2019), skills (Kulkarni and Khandale, 2019), improves health balance in patients with neuropathies (Panse et al., 2018), improves concentration for online learning (Pratiwi and Pratama, 2020; Anggraini and Dewi, 2022), and reduction of fatigue and muscle pain (Ismayenti et al., 2021) among other research that indicates the positive contribution of this method.

In Latin America, little research has been carried out regarding the performance of students in Mathematics with Brain Gym. This study makes an important contribution to the line of research that seeks to improve mathematics performance in the basic educational context, since there is a very low level of performance in this subject in the region. This study is novel since it seeks to verify the effectiveness of the Brain Gym technique through a study with a quasi-experimental scope, which will allow contrasting the benefit of its application in favor of mathematical skills. For this reason, this study seeks to address four key elements of learning Mathematics: (a) the definition and elements of rational numbers, (b) problem-solving, (c) order relation and (d) equivalent fractions, which with the application of the Brain Gym program, through systematical exercises, the neuronal connections of the cerebral hemispheres are stimulated, significantly strengthening and improving the learning process.

Investigation hypotheses

> *H1*: The group of students that will receive the intervention procedure in Brain Gym will present better results in definition and elements of rational numbers when compared in the post-test measurement with the students of the control group.
>
> *H2*: The group of students from the experimental group that will receive the Brain Gym intervention will have a higher level of problem-solving when compared in the post-test assessment with the students from the control group.
>
> *H3*: The students of the experimental group will present higher levels concerning order when compared in the post-test with the students of the control group.
>
> *H4*: The students of the group that receives the intervention with Brain Gym, will present better levels in equivalent fractions when compared in the post-test with the students of the control group.

Materials and methods

Research design

In this research, a quasi-experimental research design was used. Participants were divided into two groups, one that received a Brain Gym intervention and one that was a comparison control group.

Sample

Two groups of the same level of education were randomly chosen with a total of 67 students, 35 (52%) females, and 32 (48%) males. The age of the participants was from 12 to 14 years old. The experimental group consisted of 35 students, 15 males, and 20 females. The control group was made up of 32 students, 17 males, and 15 females. Both the experimental and control groups had the same sociodemographic, economic, educational, and social characteristics. The characteristics of both groups matched.

In the G*Power program (Heinrich Heine Universität Düsseldorf, 2022) based on the sample size of 65 participants and with the parameters of median effect size 0.15, error probability of .05, 2 groups and 4 measurements made, it was found that, the study with the sample that worked has an adequate statistical power of $1\text{-}\beta = 0.82$.

Measurements

The instruments used to support the research data were conducted through a test that was made up of 12 components that measured the knowledge of the four topics of rational numbers, which were then checked by experts in Mathematics. These were in the Forms app, to be applied online to the experimental group and the control group before and after the intervention.

Intervention protocol

The intervention consisted of a program made up of Brain Gym exercises aligned to improve the learning of Mathematics. Then, they were organized based on the PACE process and incorporated into the pedagogical day during the sessions that the intervention program lasted. In the intervention with the experimental group, a series of Brain Gym exercises were carried out that allowed the student to generate a better brain function to perform in mathematics.

The exercises performed were: (a) crossed crawl, consisted of energetically touching the left knee with the right elbow and in a contrary way. This exercise allowed the activation of the brain to improve visual, auditory, kinesiological and tactile abilities. (b) The owl, puts its hand on the shoulder of the opposite side, squeezing it firmly and turns its head towards that side. The student must take a deep breath and exhale by turning the head towards the opposite shoulder. The same is done with the other side (Dennison, 1992; Kulkarni and Khandale, 2019).

The next exercise in the intervention program was: (c) double scribbling, in which the student must draw with both hands at the same time, in, out, up, and down. This exercise benefits writing and fine motor skills. (d) Buttons of the brain, one hand is placed on the navel and with the other hand imaginary buttons must be drawn at the junction of the clavicle with the sternum, making circular movements in a clockwise direction. These exercises stimulate the eyesight and improve bilateral coordination (Dennison, 1992; Murtadho et al., 2019).

Subsequently, the exercises were applied: (e) energetic yawning, where the fingertips are placed on the cheeks, a yawn is simulated and pressure is applied with the fingers. This exercise stimulates verbal expression and communication. The brain is oxygenated, relaxes tension in the facial area and improves visual perception. (f) Eight lazy or lying down, a large eight must be drawn horizontally or with pencil and paper. Begin to draw the center and continue to the left, return to the center and finish on the right side. Finally, (g) thinking hat, you should put your hands on your ears and try to follow the shape of the ear from the ear canal out. These exercises help listening skills, improve attention, verbal fluency and balance (Dennison, 1992; Pratiwi and Pratama, 2020). Table 1 describes the applied protocol.

The intervention lasted 8 weeks within the mathematics class of two courses. This process was carried out during the online class process, where the execution of the exercises was explained to the students of the control group. In each of the sessions, the students were supervised by their parents and the teacher on the correct execution of the Brain Gym exercises performed. In Figure 1 you can see images of the intervention performed.

Procedure

The investigation began with the approval from the authority of the institution and the ethics committee of the Indoamerica University of Ecuador. Two groups of the same educational level, an experimental group, and a control group were randomly chosen. The intervention program began with the application of a pre-test to the two groups, who had knowledge of the four key elements of Mathematics. Then, the Brain Gym program was applied for eight sessions. Once the intervention program finished, they were evaluated with a post-test with the same knowledge that was measured at the beginning.

Statistical analysis

The analysis began with descriptive statistics to characterize the quantitative results of the participants. After that, a 2×2 ANOVA was done. The control and experimental groups were considered as two levels of the factors between them. In the intra-group factor, the two pre and post-test levels were considered. The comparisons with the Bonferroni statistic were used as a model adjustment and the level of significance was valued at $p < 0.05$. All analyzes were performed in the SPSS version 28 program. These analyses were carried out in the statistical package SPSS v. 25.

TABLE 1 Brain Gym intervention protocol.

Sessions	Objectives	Experimental group activities	Control group activities	Means	Time (min)
First	Diagnose the level of knowledge by applying an evaluation on rational numbers	Apply initial evaluation on rational numbers	Apply initial evaluation on rational numbers	Test in forms	40
Second	Recognize the set of Q rational numbers and identify their elements	Using the Brain Gym program, the set of rational numbers and their elements are presented	Presentation of the set of rational numbers and their elements passively and traditionally	Internet power point presentation	40
Third	Establish order relationships using the number line	Applying the Brain Gym program, fractions are located on the number line	Location of fractions on the number line passively and traditionally	Internet number line	40
Fourth	Solve rational numbers through problem-solving	Using the Brain Gym program, the problem-solving method is applied	Application of the method for solving problems passively and traditionally	Internet white board markers	40
Fifth	Establish equivalent fractions from a fraction	Applying the Brain Gym program, equivalent fractions are done	Construction of equivalent fractions through amplification passively and traditionally	Internet PhET tool	40
Sixth	Form irreducible fractions from simplification	Fractions are simplified using the Brain Gym program	Simplification of fractions passively and traditionally	Internet white board sheets	40
Seventh	Establish order relationships in a set of rational numbers	Using the Brain Gym program, equivalent fractions are done	Construction of equivalent fractions passively and traditionally	Internet video	40
Eighth	Evaluate the level of knowledge by applying an evaluation on rational numbers	Apply final evaluation on rational numbers	Apply final evaluation on rational numbers	Test in forms	40

The study scenario

This study was conducted in the capital of Ecuador, the city of Quito. Ecuador is a middle-income developing country located in South America. Ecuador has an approximate population of 17 million inhabitants, while the city of Quito has, in its metropolitan area, a population close to 3 million inhabitants. Ecuador's economic system is based on the private property model, and its official currency is the U.S. dollar (National Institute of Statistics and Censuses (INEC), Ecuador, 2013; National Institute of Educational Evaluation (INEE), Ecuador, 2019). Thus, the following presented results could be useful not solely in the context in which this research took place but also in other contexts that share similar described characteristics.

Results

In the first place, the reliability of all the measurements carried out was calculated, for which the Cronbach's Alpha statistic was used. Acceptable levels of internal consistency were found in this analysis. In addition, it was found that the items that build each of the variables were significantly correlated and contributed in favor of the construction of each scale. The reliability results of each variable are: definition and elements of post-test rational numbers $\alpha = 0.71$, problem-solving pre-test $\alpha = 0.75$, Post-test problem-solving $\alpha = 0.78$, pre-test Order Relation $\alpha = 0.70$, post-test Order Relation $\alpha = 0.70$, pre-test equivalent fractions $\alpha = 0.76$ and post-test equivalent fractions $\alpha = 0.70$. Table 2 shows the descriptive results obtained by the control and intervention groups in the 4 variables assessed.

Regarding the first hypothesis: the group of students belonging to the experimental group present higher levels in definition and elements when compared to the students of the control group. In the ANOVA, it was found that there are no differences in the interaction between the intervention and the pre and post-test measurement time $F_{(1,65)} = 0.83$, $p = 0.36$, $\eta^2 = 0.013$. Significant effects of the technological intervention were found on the definition and elements of rational number items $F_{(1,65)} = 3014.05$, $p = <0.001$, $\eta^2 = 0.98$. Figure 2 shows the comparison.

Regarding the second hypothesis, which indicates that the participants of the experimental group will have higher levels of problem-solving, a significant interaction was found with the best levels of problem-solving in favor of the experimental group $F_{(1,65)} = 8.76$, $p = 0.04$, $\eta^2 = 0.12$. In main effects, it was found that different approaches used with the experimental group positively influence the problem-solving ability of the students $F_{(1,65)} = 3523.57$, $p = <0.001$, $\eta^2 = 0.98$. Figure 3 shows the graph of the comparison.

Concerning the third hypothesis that stated that the students who received the different approaches would improve in relation to the order relation, it was found that there is no interaction between the intervention and the dependent variable $F_{(1,65)} = 1.44$, $p = 0.23$, $\eta^2 = 0.22$. Concerning the main effects of the intervention on the order relation, statistically significant results were found

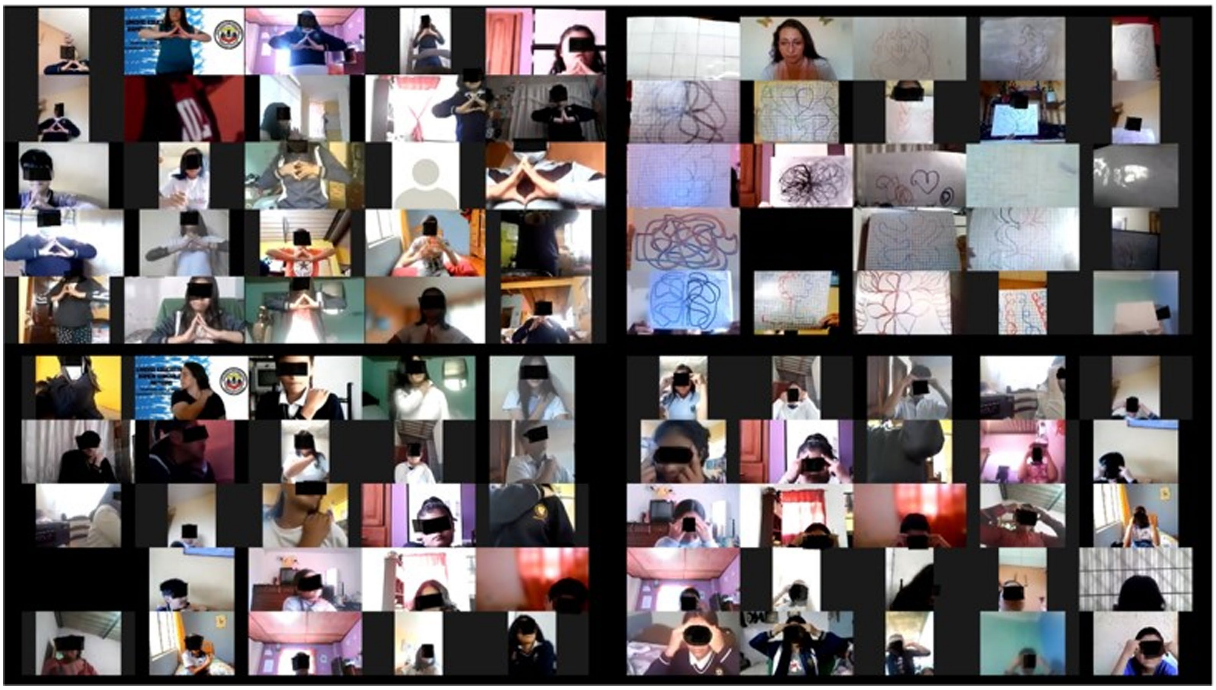

FIGURE 1
Execution of Brain Gym exercises.

TABLE 2 Descriptive statistics.

	Group	Mean	SD
Definition and elements of rational	Experimental group	7,6,000	1.94331
numbers pre-test	Control group	7.5313	1.56544
Definition and elements of post-test	Experimental group	8,5,714	0.88403
rational numbers	Control group	8,0938	1.39952
Problem-solving pre-test	Experimental group	6.1143	1.07844
	Control group	6.0625	1.21649
Post-test problem-solving	Experimental group	7,4,000	1.49902
	Control group	5.9375	1.41279
Pre-test order relation	Experimental group	6,4,000	1.45925
	Control group	6.0625	1.21649
Post-test order relation	Experimental group	7.7143	1.34101
	Control group	6.8125	1.40132
Pre-test equivalent fractions	Experimental group	6.9143	1.50238
	Control group	6.7188	1.61114
Post-test equivalent fractions	Experimental group	8,4,286	0.88403
	Control group	7.3125	1.76777

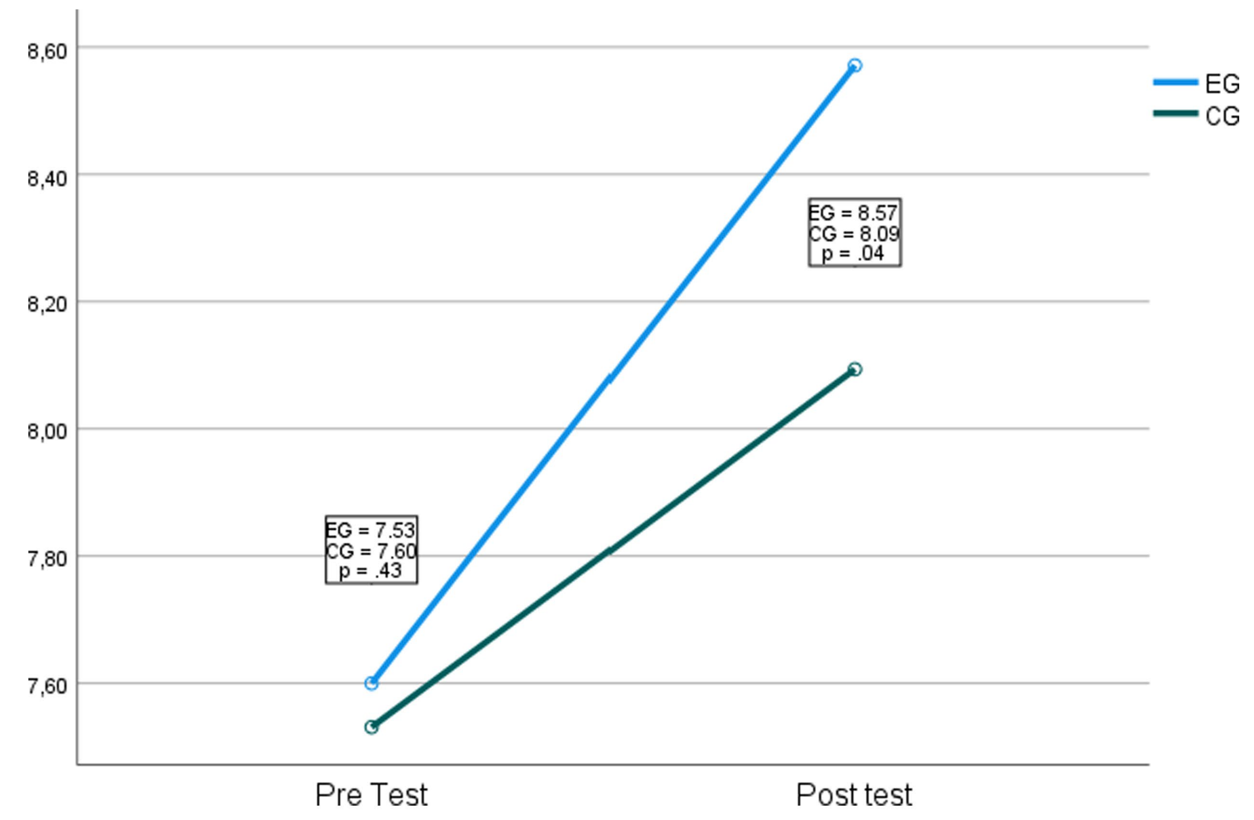

FIGURE 2
Comparison of the control and experimental groups in definition and elements.

$F_{(1,65)} = 3283.56$, $p = <0.001$, $\eta^2 = 0.96$. Figure 4 shows the comparison.

Regarding the fourth hypothesis, which states that the students in the experimental group have better results in fractions when compared to the control group, a statistically significant interaction was found between the approaches and the best results in fractions with the students in the experimental group $F_{(1,65)} = 4.54$, $p = 0.03$, $\eta^2 = 0.06$. Regarding the main effects, statistically significant results were found with the different approaches and performance in fractions

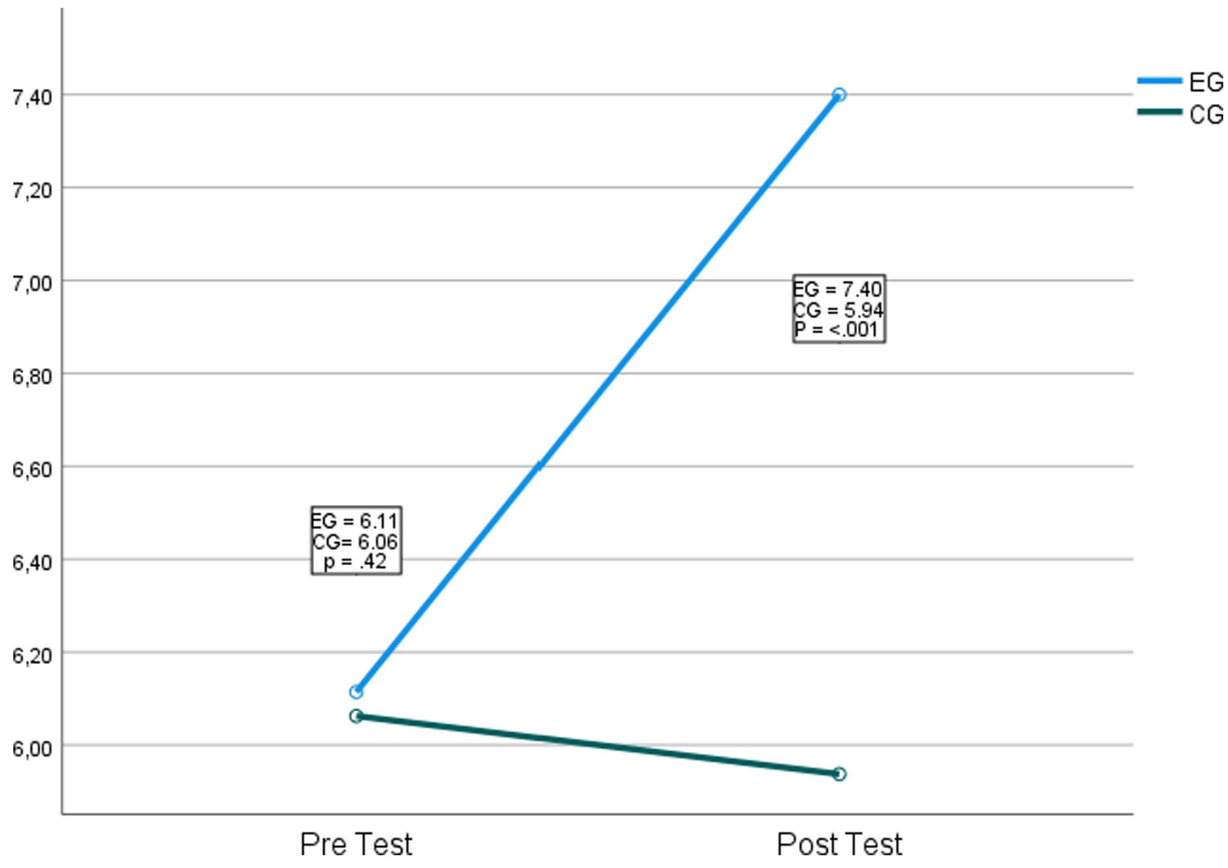

FIGURE 3
Comparison of the control and experimental groups in problem-solving.

$F_{(1,65)} = 2612.56$, $p = <0.001$, $\eta^2 = 0.97$. Figure 5 shows the comparison.

An analysis was carried out considering the influence of gender on the measurements made. It was found that there is no statistically significant association between gender and definition and elements pre-test (x^2 =, $p = 21$) and post-test ($x^2 = 5.75$, $p = 0.33$), order relation pre-test ($x^2 = 4.39$, $p = 0.62$) and post-test ($x^2 = 7.24$, $p = 0.20$), equivalent fractions pre-test ($x^2 = 8.19$, $p = 0.22$) and post-test ($x^2 = 6.96$, $p = 0.32$). When relating gender to problem solving, a statistically significant association was found with problem solving pre-test ($x^2 = 12.09$, $p = 0.03$) and post-test ($x^2 = 12.81$, $p = 0.04$). Figure 6 shows the problem solving score according to the gender of the participants.

Discussion

In the present investigation, the impact of Brain Gym on the learning process of Mathematics was demonstrated through the application of a quasi-experimental investigation measuring the understanding, definition, and knowledge of the elements of rational numbers, their order relation, equivalent fractions, and problem-solving. In the intervention process, an experimental group received different approaches using Brain Gym methods. On the other hand, with the control group, a traditional and passive methodology was used.

It is important to consider that Brain Gym which is an active strategy that allows the stimulation of the neuronal connections through the interaction of body–brain movement, allowed to increase neuroplasticity which at the same time significantly improved and benefited the learning process of the contents of rational numbers.

The results obtained in the research provide empirical evidence in favor of the hypotheses raised in this research regarding learning Mathematics better, specifically, the knowledge of rational numbers. When comparing the results between the experimental group and the control group, a significant difference is shown through the pre-test, the application of the Brain Gym program, and the post-test. In addition, the two groups improved their learning, nevertheless, in the control group, it does not significantly increase the way it does in the experimental group.

The results of this research are consistent with other previously conducted studies where the benefits of Brain Gym in the learning process of Mathematics are demonstrated. According to

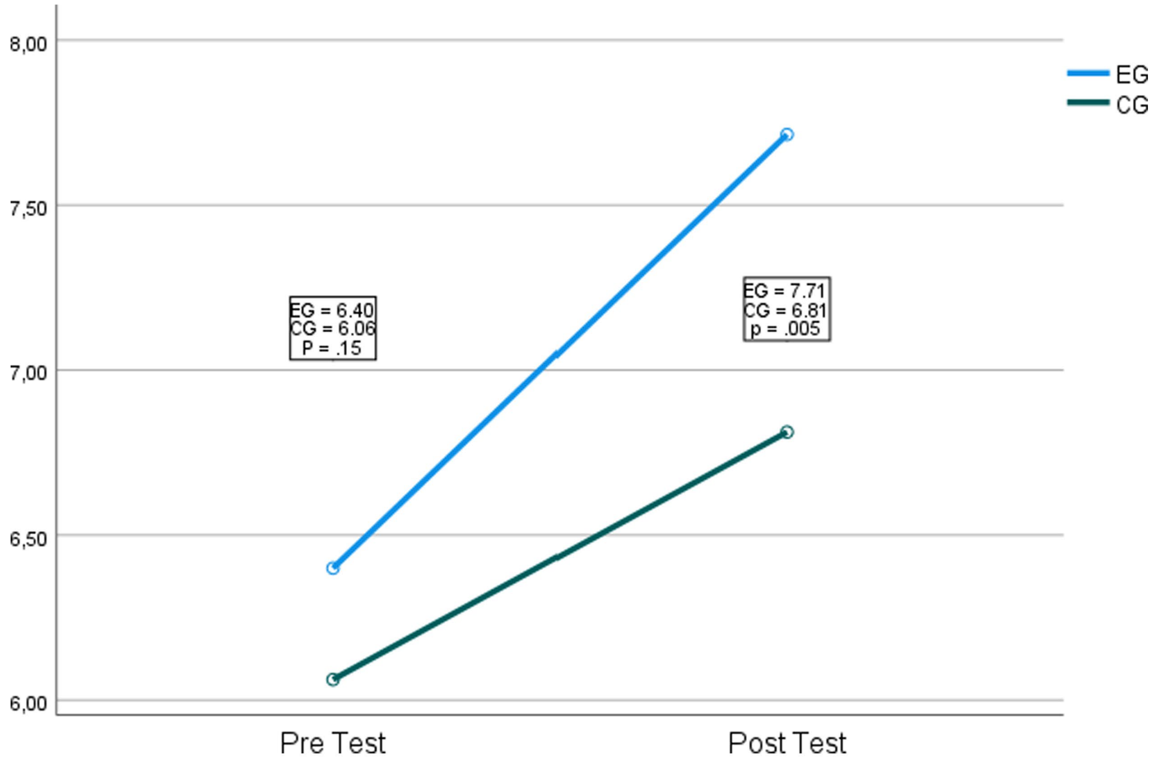

FIGURE 4
Comparison of the control and experimental groups concerning order.

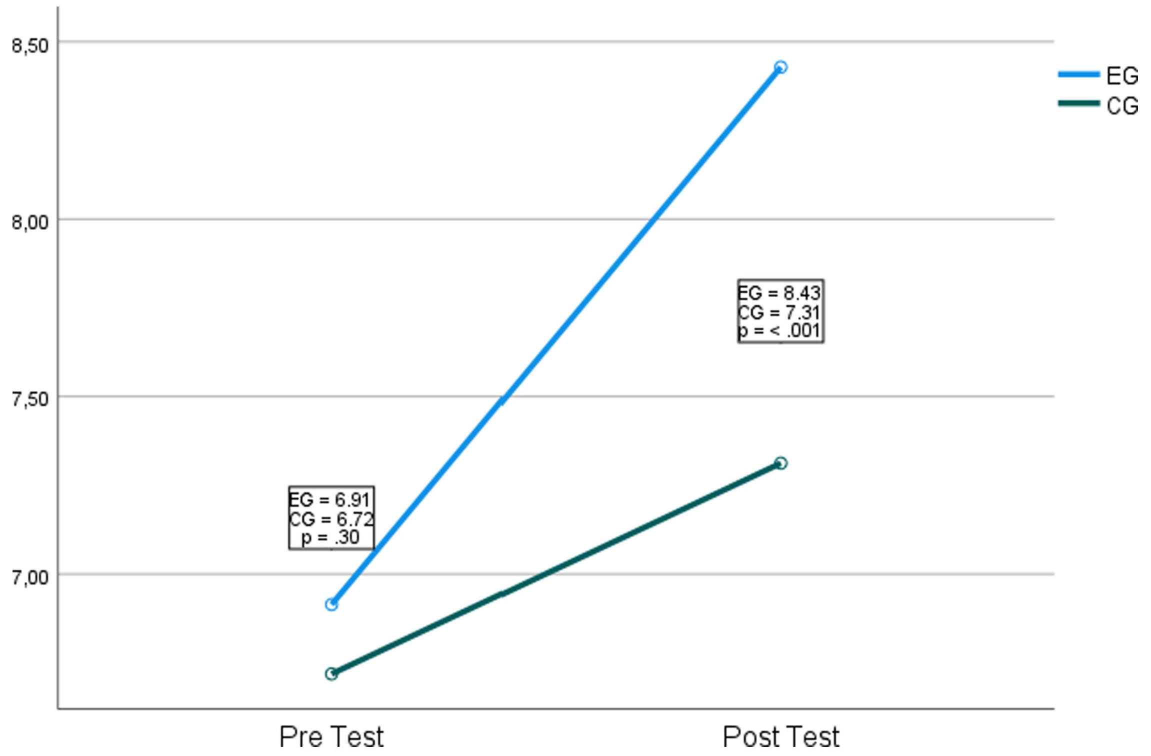

FIGURE 5
Comparison of the control and experimental groups in fractions.

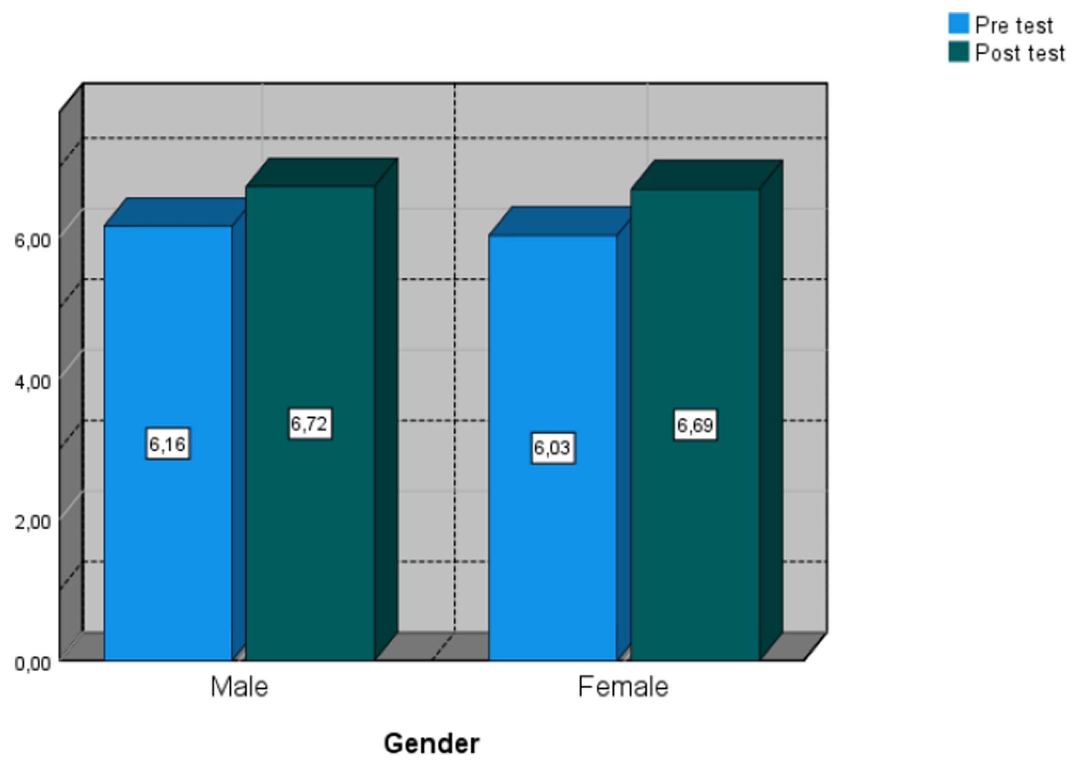

FIGURE 6
Scores in solving mathematical problems found in the pre- and post-test measurements.

Colina et al. (2021) and Romero et al. (2021), with the Brain Gym program, the improvement of the learning process in students is obtained with positive, tangible, and measurable results, causing progress in all areas of knowledge.

In addition, the results found in this research would be explained by the benefit of the Brain Gym in cognitive skills such as attention, perception and memory of the human being, which could have influenced the better performance of the experimental group in the assessment of mathematics carried out after the intervention, since by improving the brain state of the student to attend to and process information better, they will have a better performance in a developing cognitive skill involved in mathematical thinking (Watson and Kelso, 2014; Cano-Estrada et al., 2022).

Several cognitive functions would benefit from the use of the Brain Gym in the experimental group of this research. For example, it is indicated that with the applied exercises levels of visual perception, concentration, hearing capacity, speed in problem solving, better brain state to generate neuronal interconnections and motor capacity would be improved. This cognitive difference would explain the better performance of the group that received the intervention with Brain Gym, which motivates us to continue carrying out new studies in favor of this technique that can benefit students in Latin America (Murtadho et al., 2019; Colina et al., 2021).

The limitations of the research were the difficulty of generating a random assignment of participants in each of the groups since the courses had been previously established, yet an attempt to go around this was to randomly select two groups.

In the future, and based on the results obtained in this research, it's proposed to use Brain Gym at other levels of education. In hypothesis, in further research, the use of these types of approaches will bring benefits to complex and essential knowledge in Mathematics such as functions, algebra, geometry, measurement, statistics, and probabilities.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Comité de Ética de la Universidad Indoamérica de Ecuador. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

CR-G: conceptualization, investigation, formal analysis, writing original draft, review and editing, and project administration. CA-V: investigation, writing original draft, and formal analysis. JC-C: investigation, formal analysis, and review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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Challenges of teachers when teaching sentence-based mathematics problem-solving skills

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Sentence-based mathematics problem-solving skills are essential as the skills can improve the ability to deal with various mathematical problems in daily life, increase the imagination, develop creativity, and develop an individual's comprehension skills. However, mastery of these skills among students is still unsatisfactory because students often find it difficult to understand mathematical problems in verse, are weak at planning the correct solution strategy, and often make mistakes in their calculations. This study was conducted to identify the challenges that mathematics teachers face when teaching sentence-based mathematics problem-solving skills and the approaches used to address these challenges. This study was conducted qualitatively in the form of a case study. The data were collected through observations and interviews with two respondents who teach mathematics to year four students in a Chinese national primary school in Kuala Lumpur. This study shows that the teachers have faced three challenges, specifically low mastery skills among the students, insufficient teaching time, and a lack of ICT infrastructure. The teachers addressed these challenges with creativity and enthusiasm to diversify the teaching approaches to face the challenges and develop interest and skills as part of solving sentence-based mathematics problems among year four students. These findings allow mathematics teachers to understand the challenges faced while teaching sentence-based mathematics problem solving in depth as part of delivering quality education for every student. Nevertheless, further studies involving many respondents are needed to understand the problems and challenges of different situations and approaches that can be used when teaching sentence-based mathematics problem-solving skills.

KEYWORDS
mathematics, problem solving, teaching challenges, teaching approaches, primary school

1. Introduction

To keep track of the development of the current world, education has changed over time to create a more robust and effective system for producing a competent and competitive generation (Hashim and Wan, 2020). The education system of a country is a significant determinant of the growth and development of the said country (Ministry of Education Malaysia, 2013). In the Malaysian context, the education system has undergone repeated changes alongside the latest curriculum, namely the revised Primary School Standard Curriculum (KSSR) and the revised Secondary School Standard Curriculum (KSSM). These changes have been implemented to ensure that Malaysian education is improving continually so then the students can guide the country to compete globally (Adam and Halim, 2019). However, Malaysian students have shown limited skills in international assessments such as Trends in International Mathematics and Science Study (TIMSS) and the Program for International Student Assessment (PISA).

According to the PISA 2018 results, the students' performance in mathematics is still below the average level of the Organization for Economic Co-operation and Development (OECD; Avvisati et al., 2019). The results show that almost half of the students in Malaysia have still not mastered mathematical skills fully. Meanwhile, the TIMSS results in 2019 have shown there to be a descent in the achievements of Malaysian students compared to the results in 2015 (Ministry of Education Malaysia, 2020b). This situation is worrying as most students from other countries such as China, Singapore, Korea, Japan, and others have a higher level of mathematical skills than Malaysian students. According to Mullis et al. (2016), these two international assessments have in common that both assessments test the level of the students' skills when solving real-world problems. In short, PISA and TIMSS have proven that Malaysian students are still weak when it comes to solving sentence-based mathematics problems.

According to Hassan et al. (2019), teachers must emphasize the mastery of sentence-based mathematics problem-solving skills and apply it in mathematics teaching in primary school. Sentence-based mathematics problem-solving skills can improve the students' skills when dealing with various mathematical problems in daily life (Gurat, 2018), increase the students' imagination (Wibowo et al., 2017), develop the students' creativity (Suastika, 2017), and develop the students' comprehension skills (Mulyati et al., 2017). The importance of sentence-based mathematic problem-solving skills is also supported by Ismail et al. (2021). They stated that mathematics problem-solving skills are similar to high-level thinking skills when it comes to guiding students with how to deal with problems creatively and critically. Moreover, problem-solving skills are also an activity that requires an individual to select an appropriate strategy to be performed by the individual to ensure that movement occurs between the current state to the expected state (Sudarmo and Mariyati, 2017). There are various strategies that can be used by teachers to guide students when developing their problem-solving skills such as problem-solving strategies based on Polya's Problem-Solving Model (1957). Various research studies have used problem-solving models to solve specific problems to improve the students' mathematical skills. Polya (1957), Lester (1980), Gick (1986), and DeMuth (2007) are examples. One of the oldest problem-solving models is the George Polya model (1957). The model is divided into four major stages: (i) understanding the problem; (ii) devising a plan that will lead to the solution; (iii) Carrying out the plan; and (iv) looking back. In contrast to traditional mathematics classroom environments, Polya's Problem-Solving Process allows the students to practice adapting and changing strategies to match new scenarios. As a result, the teachers must assist the students to help them recognize whether the strategy is appropriate, including where and how to apply the technique.

In addition, problem-solving skills are one of the 21st-century skills that need to be mastered by students through education now so then they are prepared to face the challenges of daily life (Khoiriyah and Husamah., 2018). This statement is also supported by Widodo et al. (2018) who put forward four main reasons why students need to master problem-solving skills through mathematics learning. One reason is that sentence-based mathematics problem-solving skills are closely related to daily life (Wong, 2015). Such skills can be used to formulate concepts and develop mathematical ideas, a skill that needs to be conveyed according to the school's content standards. The younger generation is expected to develop critical, logical, systematic, accurate, and efficient thinking when solving a problem. Accordingly, problem solving has become an element that current employers emphasize when looking to acquire new energy sources (Zainuddin et al., 2018). This clearly shows that problem-solving skills are essential skills that must be mastered by students and taken care of by mathematics teachers in primary school.

In the context of mathematics learning in Malaysia, students are required to solve sentence-based mathematics problems by applying mathematical concepts learned at the end of each topic. Two types of sentence-based mathematics problems are presented when teaching mathematics: routine and non-routine (Wong and Matore, 2020). According to Nurkaeti (2018), routine sentence-based math problems are questions that require the students to solve problems using algorithmic calculations to obtain answers. For non-routine sentence-based math problems, thinking skills and the ability to apply more than one method or solution step are needed by the student to solve the problem (Shawan et al., 2021). According to Rohmah and Sutiarso (2018), problem-solving skills when solving a non-routine sentence-based mathematical problem is a high-level intellectual skill where the students need to use logical thinking and reasoning. This statement also aligns with Wilson's (1997) opinion that solving non-routine sentence-based mathematics always involves high-order thinking skills (HOTS). To solve non-routine and HOTS fundamental sentence-based math problems, a student is required to know various problem-solving strategies for solving the problems (Wong and Matore, 2020). This situation has indirectly made the mastery of sentence-based mathematics problem-solving skills among students more challenging (Mahmud, 2019).

According to Alkhawaldeh and Khasawneh's findings (2021), the failure of students stems from the teachers' inability to perform their role effectively in the classroom. This statement is also supported by Abdullah (2020). He argues that the failure of students in mastering non-routine sentence-based mathematics problem-solving skills is due to the teachers rarely supplying these types of questions during the process of learning mathematics in class. A mathematics teacher should consider this issue because the quality of their teaching will affect the students' mastery level of sentence-based mathematics problem-solving skills.

In addition, the teachers' efforts to encourage the students to engage in social interactions with the teachers (Jatisunda, 2017) and the teachers' method of teaching and assessing the level of sentence-based mathematics problem-solving skills (Buschman, 2004) are also challenges that the teachers must face. Strategies that are not appropriate for the students will affect the quality of delivery of the sentence-based mathematics problem-solving skills as well as cause one-way interactions to exist in the classroom. According to Rusdin and Ali (2019), a practical teaching approach plays a vital role in developing the students' skills when mastering specific knowledge. However, based on previous studies, the main challenges that mathematics teachers face when teaching sentence-based mathematics problem solving are due to the students. These challenges include the students having difficulty understanding sentence-based math problems, lacking knowledge about basic mathematical concepts, not calculating accurately, and not transforming the sentence-based mathematics problems into an operational form (Yoong and Nasri, 2021). This also means that they cannot transform the sentence-based math problems into an operational form (Yoong and Nasri, 2021). As a result, the teacher should diversify his or her teaching strategy by emphasizing understanding the mathematical concepts rather than procedural teaching to reinforce basic mathematical concepts, to encourage the students to work on any practice problems assigned by the teacher before completing any assignments to help them do the calculation correctly, and engaging in the use of effective oral questioning to stimulate student thinking related to the operational need when problem solving. All of these strategies actually help the teachers facilitate and lessen the students' difficulty understanding sentence-based math problems (Subramaniam et al., 2022).

Meanwhile, Dirgantoro et al. (2019) stated several challenges that the students posed while solving the sentence-based problem. For example, students do not read the questions carefully, the students lack mastery of mathematical concepts, the students solve problems in a hurry due to poor time management, the students are not used to making hypotheses and conclusions, as well as the students, being less skilled at using a scientific calculator. These factors have caused the students to have difficulty mastering sentence-based mathematics problem-solving skills, which goes on to become an inevitable challenge in maths classes. Therefore, teachers need to study these challenges to self-reflect so then their self-professionalism can be further developed (Dirgantoro et al., 2019).

As for the school factor, challenges such as limited teaching resources, a lack of infrastructure facilities, and a large number of students in a class (Rusdin and Ali, 2019) have meant that a conducive learning environment for learning sentence-based mathematics problem-solving skills cannot be created. According to Ersoy (2016), problem-solving skills can be learned if an appropriate learning environment is provided for the students to help them undergo a continuous and systematic problem-solving process.

To develop sentence-based mathematics problem-solving skills among students, various models, pedagogies, activities, etc. have been introduced to assist mathematics teachers in delivering sentence-based mathematics problem-solving skills more effectively (Gurat, 2018; Khoiriyah and Husamah., 2018; Özreçberoğlu and Çağanağa, 2018; Hasibuan et al., 2019). However, students nowadays still face difficulties when trying to master sentence-based mathematics problem-solving skills. This situation occurs due to the lack of studies examining the challenges faced by these mathematics teachers and how teachers use teaching approaches to overcome said challenges. This has led to various issues during the teaching and facilitation of sentence-based mathematics problem-solving skills in mathematics classes. According to Rusdin and Ali (2019), these issues need to be addressed by a teacher wisely so then the quality of teaching can reach the best level. Therefore, mathematics teachers must understand and address these challenges to improve their teaching.

However, so far, not much is known about how primary school mathematics teachers face the challenges encountered when teaching sentence-based mathematics problem-solving skills and what approaches are used to address the challenges in the context of education in Malaysia. Therefore, this study needs to be carried out to help understand the teaching of sentence-based mathematics problem-solving skills in primary schools (Pazin et al., 2022). Due to the challenges when teaching mathematics as stipulated in the Mathematics Curriculum and Assessment Standard Document (Ministry of Education Malaysia, 2020a) which emphasizes mathematical problem-solving skills as one of the main skills that students need to master in comprehensive mathematics learning, this study focuses on identifying the challenges faced by mathematics teachers when teaching sentence-based mathematics problem-solving skills and the approaches that mathematics teachers have used to overcome those challenges. The results of this study can provide information to mathematics teachers to help them understand the challenges when teaching sentence-based mathematics problem-solving skills and the approaches that can be applied to overcome the challenges faced. Therefore, it is very important for this study to be carried out so then all the visions set within the framework of the Malaysian National Mathematics Curriculum can be successfully achieved.

2. Conceptual framework

The issue of students lacking mastery of sentence-based mathematics problem-solving skills is closely related to the challenges that teachers face and the teaching approach used. Based on the overall findings of the previous studies, the factors that pose a challenge to teachers when delivering sentence-based mathematics problem-solving skills include challenges from the teacher (Buschman, 2004; Jatisunda, 2017; Abdullah, 2020), challenges from the pupils (Dirgantoro et al., 2019), and challenges from the school (Rusdin and Ali, 2019). As for the teaching approach, previous studies have suggested teaching approaches such as mastery learning, contextual learning, project-based learning, problem-based learning, simulation, discovery inquiry, the modular approach, the STEM approach (Curriculum Development Division, 2019), game-based teaching which uses digital games (Muhamad et al., 2018), and where a combination of the modular approach especially the flipped classroom is applied alongside the problem-based learning approach when teaching sentence-based mathematics problem solving (Alias et al., 2020). This is as well as the constructivism approach (Jatisunda, 2017). The conceptual framework in Figure 1 illustrates that the teachers will face various challenges during the ongoing teaching and facilitation of sentence-based mathematics problem-solving skills.

3. Methodology

The objective of this study was to determine the challenges that teachers face while teaching sentence-based mathematics problem-solving skills and the approaches used when teaching those skills. Therefore, a qualitative research approach in the form of a case study was used to collect data from the participants in a Chinese national type of school (SJKC) in Bangsar and Pudu, in the Federal Territory of Kuala Lumpur. The school, SJKC, in the districts of Bangsar and Pudu, was chosen as the location of this study because the school is implementing the School Transformation Program 2025 (TS25). One of the main objectives of the TS25 program is to apply the best teaching concepts and practices so then the quality of the learning and teaching in the classes is improved. Thus, schools that go through the program are believed to be able to diversify their teachers' teaching and supply more of the data needed to answer the questions of this study. This is because case studies can develop an in-depth description and analysis of the case to be studied (Creswell and Poth, 2018). All data collected through the observations, interviews, audio-visual materials, documents, and reports can be reported on in terms of both depth and detail based on the theme of the case. Therefore, this study collected data related to the challenges and approaches of SJKC mathematics teachers through observations, interviews, and document analysis.

Two primary school mathematics teachers who teach year four mathematics were selected to be the participants of this research using the purposive sampling technique to identify the challenges faced and the approaches used to overcome those challenges. The number of research participants in this study was sufficient enough to allow the researcher to explore the real picture of the challenges found when teaching sentence-based mathematics problem-solving skills and the approaches that can be applied when teaching to overcome the challenges faced. According to Creswell and Creswell (2018), the small number of study participants is sufficient when considering that the main purpose of the study is to obtain findings that can give a holistic and meaningful picture of the teaching and learning process in the classroom. However, based on the data analysis for both study participants, the researcher

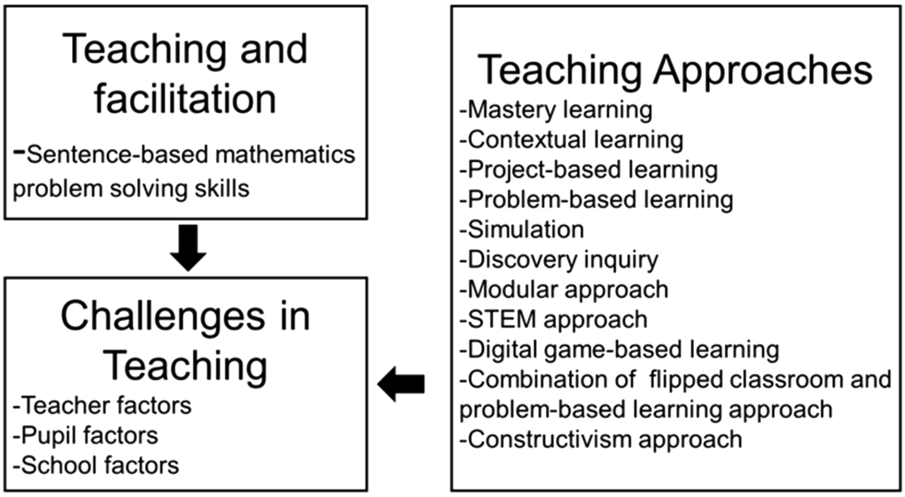


FIGURE 1
Conceptual framework of the study.

considered repeated information until it reached a saturation point. The characteristics of the study participants required when they were supplying the information for this study were as follows:

i. New or experienced teachers.
ii. Year four math teacher.
iii. Teachers teach in primary schools.
iv. The teacher teaches the topic of sentence-based mathematics problem-solving skills.

The types of instruments used in the study were the observation protocol, field notes, interview protocol, and participants' documents. In this study, the researcher used participatory type observations to observe the teaching style of the teachers when engaged in sentence-based mathematics problem-solving skills lessons. Before conducting the study, the researcher obtained consent to conduct the study from the school as well as informed consent from the study participants to observe their teaching. During the observation, the teacher's teaching process was recorded and transcribed using the field notes provided. Then, the study participants submitted and validated the field notes to avoid biased data. After that, the field notes were analyzed based on the observation protocol to identify the teachers' challenges and teaching approaches in relation to sentence-based mathematics problem-solving skills. Throughout the observation process of this study, the researcher observed the teaching of mathematics teachers online at least four times during the 2 months of the data collection at the research location.

Semi-structured interviews were used to identify the teachers' perspectives and views on teaching sentence-based mathematics problem-solving skills in terms of the challenges faced when teaching sentence-based mathematics problem-solving skills and the approaches used by the teachers to overcome those challenges. To ensure that the interview data collected could answer the research questions, an interview protocol was prepared so then the required data could be collected from the study participants (Cohen et al., 2007). Two experts validated the interview protocol, and a pilot study was conducted to ensure that the questions were easy to understand and would obtain the necessary data. Before the interview sessions began, the participants were informed of their rights and of the related research ethics. Throughout the interview sessions, the participants were asked two questions, namely:

1. What are the challenges faced when teaching mathematical problem-solving skills earlier?
2. What teaching approaches are used by teachers when facing these challenges? Why?

Semi-structured interviews were used to interview the study participants for 30 min every interview session. The timing ensured sufficient time for both parties to complete the question-and-answer process. Finally, the entire interview process was recorded in audio form. The audio recordings were then transcribed into text form and verified by the study participants.

The types of document collected in this study included informal documents, namely the daily lesson plan documents of the study participants, the work of the students of the study participants, and any teaching aids used. All of the documents were analyzed and used to ensure that the triangulation of the data occurred between the data collected from observations, interviews, and document analysis.

All data collected through the observations, interviews, and documentary analyses were entered into the NVIVO 11 software to ensure that the coding process took place simultaneously. The data in this study were analyzed using the constant comparative analysis method including open coding, axial coding, and selective coding to obtain the themes and subthemes related to the focus of the study (Kolb, 2012). The NVIVO 11 software was also used to manage the data stack obtained from the interviews, observations, and document analysis during the data analysis process itself. In order to ensure that the themes generated from all of the data were accurate, the researcher carried out a repetitive reading process. The process of theme development involved numerous steps. First, the researcher examined the verbatim instruction data several times while looking for statements or paragraphs that could summarize a theme in a nutshell. This process had already been completed during the verbatim formation process of the teaching, while preparing the transcription. Second, the researcher kept reading (either from the same or different data), and if the researcher found a sentence that painted a similar picture to the theme that had been developed, the sentence was added to the same theme. This process is called "pattern matching" because the coding of the sentences refers to the existing categories (Yin, 2003). Third, if the identified sentence was incompatible with an existing theme, a new theme was created. Fourth, this coding procedure continued throughout each data set's theme analysis. The repeated reading process was used to select sentences able to explain the theme or help establish a new one. In short, the researcher conducted the data analysis process based on the data analysis steps proposed by Creswell and Creswell (2018), as shown in Figure 2.

4. Findings

The findings of this study are presented based on the objective of the study, which was to identify the challenges faced by teachers and the approaches used to addressing those challenges when imparting sentence-based mathematics problem-solving skills to students in year four. Several themes were formed based on the analysis of the field notes, interview transcripts, and daily lesson plans of the study participants. This study found that teachers will face challenges that stem from the readiness of students to master sentence-based mathematics problem-solving skills, the teachers' teaching style, and the equipment used for delivering sentence-based mathematics problem-solving skills. Due to facing these challenges, teachers have diversified their teaching approaches (Figure 3; Table 1).

5. Discussion

5.1. Challenges for teachers when imparting sentence-based mathematics problem-solving skills

A mathematics teacher will face three challenges when teaching sentence-based mathematics problem-solving skills. The first challenge stems from the low mastery skills held by a student. Pupils can fail to solve sentence-based mathematics problems because they have poor reading skills, there is a poor medium of instruction used, or they have a poor mastery of mathematical concepts (Johari et al., 2022). This indicates that students who are not ready or reach a minimum level of proficiency in a language, comprehension, mathematical concepts, and calculations will result in them not being able to solve sentence-based mathematics problems smoothly.

These findings are consistent with the findings of the studies by Raifana et al. (2016) and Dirgantoro et al. (2019) who showed that students who are unprepared in terms of language skills, comprehension, mathematical concepts, and calculations are likely to make mistakes when solving sentence-based mathematics problems. If these challenges are not faced well, the students will become passive and not interact when learning sentence-based mathematics problem-solving skills. This situation occurs because students who frequently make mistakes will incur low self-confidence in mathematics (Jailani et al., 2017). This situation should be avoided by teachers and social interaction should be encouraged during the learning process because the interaction between students and teachers can ensure that the learning outcomes are achieved by the students optimally (Jatisunda, 2017).

The next challenge stems from the teacher-teaching factor. This study found that how teachers convey problem-solving skills has been challenging in terms of ensuring that their students master sentence-based mathematics problem-solving skills (Nang et al., 2022). The mastery teaching approach has caused the teaching time spent on mathematical content to be insufficient. Based on the findings of this study, the allocation of time spent ensuring that the students master the skills of solving sentence-based mathematics problems through a mastery approach has caused the teaching process not to follow the rate set in the annual lesson plan.

In this study, the participants spent a long time correcting the students' mathematical concepts and allowing students to apply the skills learned. The actions of the participants of this study are in line with the statement of Adam and Halim (2019) that teachers need more time to arouse their students' curiosity and ensure that students understand

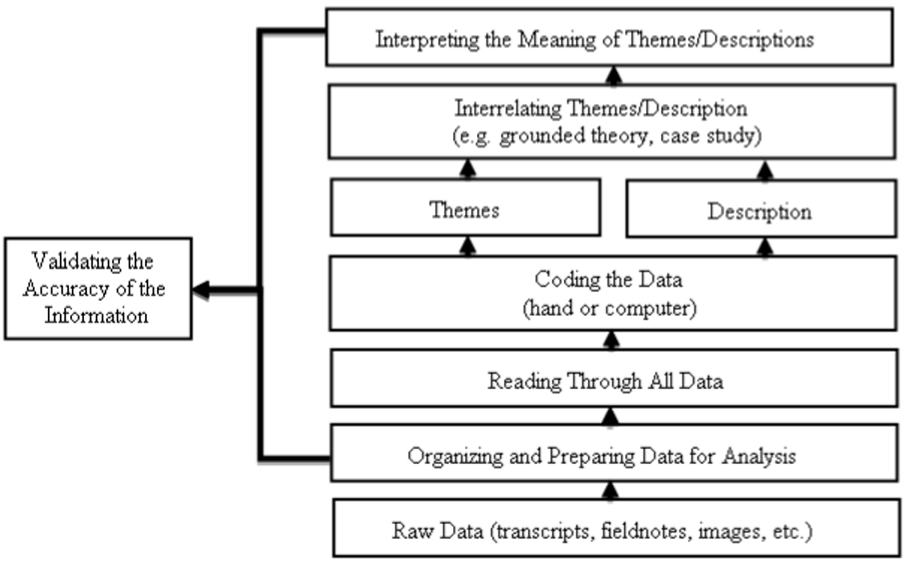


FIGURE 2
Data analysis steps (Creswell and Creswell, 2018).

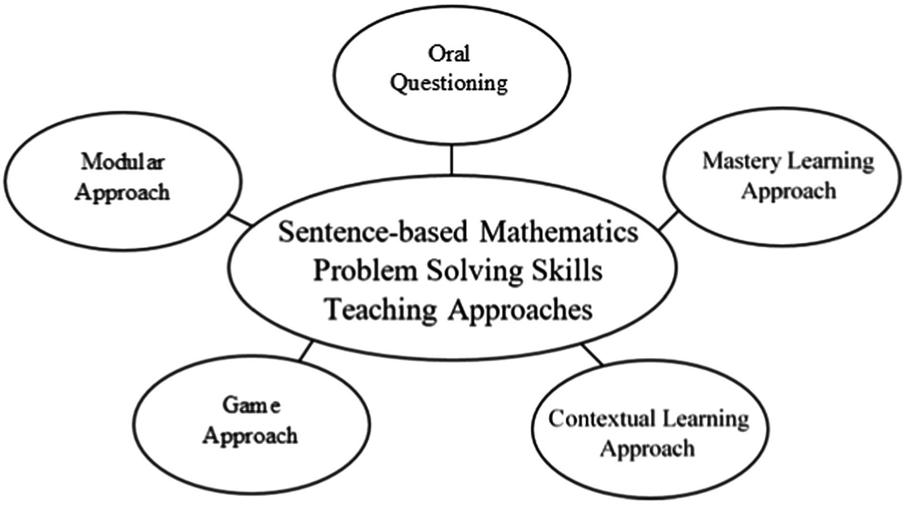


FIGURE 3
Sentence-based mathematics problem-solving teaching approaches.

the correct ideas and concepts before doing more challenging activities. However, this approach has indirectly posed challenges regarding time allocation and ensuring that the students master the skills of sentence-based mathematics problem-solving. Aside from ensuring that the students' master problem-solving skills, the participants must also complete the syllabus set in the annual lesson plan.

Finally, teachers also face challenges in terms of the lack of information and communication technology (ICT) infrastructure when implementing the teaching and facilitation of sentence-based mathematics problem-solving skills. In this study, mathematics teachers were found to face challenges caused by an unstable internet connection such as the problem of their students dropping out of class activities and whiteboard links not working. These problems have caused one mathematics class to run poorly (Mahmud and Law, 2022). Throughout the implementation of teaching and its facilitation, ICT infrastructure equipment in terms of hardware, software, and internet services has become an element that will affect the effectiveness of virtual teaching (Saifudin and Hamzah, 2021). In this regard, a mathematics teacher must be wise when selecting a teaching approach and diversifying the learning activities to implement a suitable mathematics class for students such as systematically using tables, charts, or lists, creating digital simulations, using analogies, working back over the work, involving reasoning activities and logic, and using various new applications such as Geogebra and Kahoot to help enable their students' understanding.

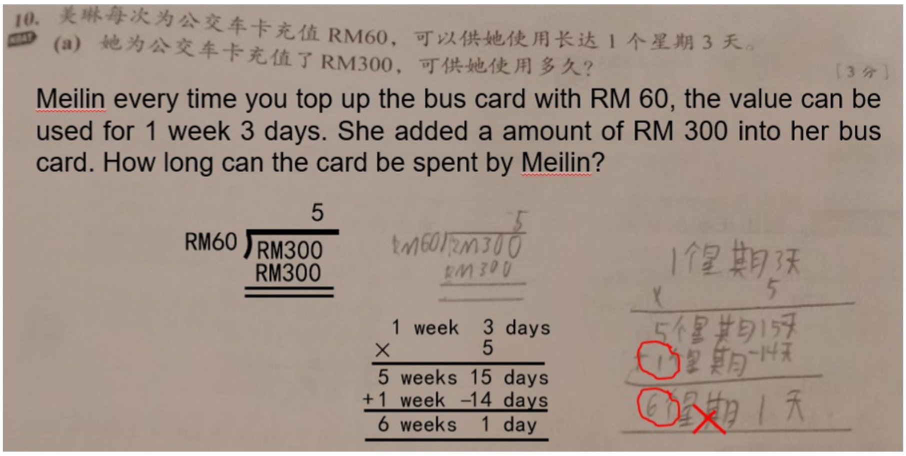
5.2. Teaching sentence-based mathematics problem-solving skills—Approaches

In this study, various approaches have been used by the teachers facing challenges while imparting sentence-based mathematics problem-solving skills. Among the approaches that the mathematics teachers have used when teaching problem-solving skills are the oral questioning approach, mastery learning approach, contextual learning approach, game approach, and modular approach. This situation has shown that mathematics teachers have diversified their teaching approaches when facing the challenges associated with teaching sentence-based mathematics problem-solving skills. This action is also in line with the excellent teaching and facilitation of mathematics proposal in the Curriculum and Assessment Standards Document revised KSSR Mathematics Year 4 (Curriculum Development Division, 2019), stating that teaching activities should be carefully planned by the teachers and combine a variety of approaches that allow the students not only to understand the content in depth but also to think at a higher level. Therefore, a teacher needs to ensure that this teaching approach is applied when teaching sentence-based mathematics problem-solving skills so then the students can learn sentence-based mathematics problem-solving teaching skills in a more fun, meaningful, and challenging environment (Mahmud et al., 2022).

Through the findings of this study, the teaching approach used by mathematics teachers was found to have a specific purpose, namely facing the challenges associated with teaching sentence-based mathematics problem-solving skills in the classroom. First of all, the oral questioning approach has been used by teachers facing the challenge of students having a poor understanding of the medium of instruction. The participants stated that questioning the students in stages can guide them to understanding the question and helping them plan appropriate problem-solving strategies. This opinion is also supported by Maat (2015) who stated that low-level oral questions could help the students achieve a minimum level of understanding, in particular remembering, and strengthening abstract mathematical concepts. The teacher's action of guiding the students when solving sentence-based mathematics problems through oral questioning has ensured that the learning takes place in a student-centered manner, providing opportunities for the students to think and solve problems independently (Mahmud and Yunus, 2018). This action is highly encouraged because teaching mathematics through the conventional approach is only effective for a short period, as the students can lack an understanding or fail to remember the mathematical concepts presented by the teacher (Ali et al., 2021).

In addition, this study also found that the participants used the mastery approach to overcome the challenges of poor reading skills and poor mastery of mathematical concepts among the students. The mastery approach was used because it can provide more opportunities and time for the students to improve their reading skills and mastery of mathematical concepts (Shawan et al., 2021). This approach has ensured

TABLE 1 Teacher challenges when teaching sentence-based mathematics problem-solving skills.

Theme	Subtheme	Evidence
Low mastery skills in the students	Low mastery of reading skills	**Teacher interview transcript**
		- Pupils cannot read and understand mathematical questions in the form of text because the student's language foundation is not good. (TB1/GM 1: 12)
		Field notes
		- Pupil K read intermittently, and the teacher gave guidance. (NL2/GM 1: 38–39)
		- Pupil Z pauses in the process of reading the mathematics question. (NL1/GM 2: 5–7)
		Student interview transcript
		I have a lot of unrecognizable words, and my Chinese is bad. English is easier than Chinese. (TB/MK: 38)
	Low mastery of the medium of instruction	**Teacher interview transcript**
		- Pupils are not able to understand the question or interpret the question in depth. (TB 1/GM 2: 10)
		Field notes
		- Pupil C has raised his problem that he still does not understand this question. (NL1/GM 1: 33–34)
		- The teacher conducts the second explanation of this question to guide students to understand the question through a question-and-answer session. (NL1/GM 1: 35–39)
		Student interview transcript
		I do not understand what this question means. (TB/MZ: 18)
	Low mastery of mathematical concepts	**Teacher interview transcript**
		- Lack of mathematical knowledge also encourages students to make mistakes in choosing strategies, especially to solve sentence-length mathematical problems, and is unclear in choosing the appropriate strategy to apply. (TB1/GM 2: 12)
		Field notes
		- Pupil W continues to object to pupil L's statement and explains that not the teacher does not allow it. The teacher has explained that the writing is incorrect because the question is multiplied by three instead of 3 days. (NL3/GM 1: 30–33)
		Student work
		
		Error in the concept of unit conversion where 1 week has 14 days

(Continued)

TABLE 1 (Continued)

Theme	Subtheme	Evidence			
Insufficient teaching time	Teaching approach used	**Teacher interview transcript**			
		- But the repeating method in teaching a topic will delay my teaching progress. (TB 1/GM 1: 24)			
		Daily lesson plan analysis			
		Participants' daily lesson plan analysis			
		Participants	**Topic**	**Period in teaching problem solving**	**Weeks**
		GM 1	4 – Time	06.09.2021–04.10.2021 (Sem Break 11.09.2021–19.09.2021)	3
		GM 2	5 – Size and Measurements	27.09.2021–08.10.2021	2
		Annual mathematics lesson plan analysis			
		Annual mathematics lesson plan			
		13 20.09.21/24.09.21	Title: 5.0 SIZE AND MEASUREMENT Standard content: 5.3 Volume of liquid	Students can: 5.3.1 Solve mathematical sentences to determine the combined operations of adding and subtracting volumes of liquids involving units in milliliters and liters 5.3.2 Solve mathematical sentences through the combined operations of multiplying and dividing the volume of a liquid involving units in milliliters and liters.	Note: Introduce the unit of liquid volume to the imperial measurement system: • Gelen (gal) • Quarter (qt) • Pain (pt) Activity suggestion: - Use objects and software for the conversion of units into a volume measurement. - Use a variety of computational strategies to solve mathematical sentences.
		14–15 27.09.21/08.10.21	Title: 5.0 SIZE AND MEASUREMENT Standard content: 5.4 Problem Solving	Students can: 5.4.1 Solve problems related to measurements in everyday situations.	Activity suggestion: Use the troubleshooting steps below: • Understand the problem. • Plan solution strategies. • Implement strategies. • Check the answers. - Use various problem-solving strategies such as reasoning logically and identifying patterns. - Use various teaching strategies such as simulations, STEM, and modular approaches.
Lack of infrastructure (ICT)	Unstable internet connection	**Field notes**			
		- Pupil H has responded that the whiteboard provided by the teacher through the link provided does not work. (NL 3/GM 1: 24–25)			
		- Pupil W took a long time, did not respond, and dropped out of class activities. (NL 4/GM 1: 50–51)			

that all students achieve the teaching objectives and that the teachers have time to provide enrichment and rehabilitation to the students as part of mastering the basic skills needed to solve sentence-based mathematics problems. This approach is very effective at adapting students to solving sentence-based mathematics problems according to the solution steps of the Polya model as well as the mathematical concepts learned in relation to a particular topic. The finding is in line with Ranggoana et al. (2018) and Mahmud (2019) study, which has shown that teaching through a mastery approach can enhance the student's learning activities. This situation clearly shows that the mastery approach has ensured that the students have time to learn at their own pace, where they often try to emulate the solution shown by the teacher to solve a sentence-based mathematics problem.

Besides that, this study also found that mathematics teachers apply contextual learning approaches when teaching and facilitating sentence-based mathematics problem-solving skills. In this study, mathematics teachers have linked non-routine problems with examples from everyday life to guide the students with poor language literacy to help them understand non-routine problems and plan appropriate solution strategies. Such relationships can help the students process non-routine problems or mathematical concepts in a more meaningful context where the problem is relevant to real situations (Siew et al., 2016). This situation can develop the students' skill of solving sentence-based math problems where they can choose the right solution strategy to solve a non-routine problem. This finding is consistent with the results of Afni and Hartono (2020). They showed that the contextual approach applied in learning could guide the students in determining appropriate strategies for solving sentence-based math problems. These findings are also supported by Seliaman and Dollah (2018) who stated that the practice of teachers giving examples that exist around the students and in real situations could make teaching and the subject facilitation easier to understand and fun.

Furthermore, the game approach was also used by the participants when imparting sentence-based mathematics problem-solving skills. According to Sari et al. (2018), the game approach to teaching mathematics can improve the student learning outcomes because the game approach facilitates the learning process and provides a more enjoyable learning environment for achieving the learning objectives. In this study, the game approach was used by the teachers to overcome the challenge of mastering the concept of unit conversion, which was not strong among the students (Tobias et al., 2015; Hui and Mahmud, 2022). The participants used the game approach to teach induction sets that guided the students in recalling mathematical concepts. The action provided a fun learning environment and attracted the students to learning mathematical concepts, especially in the beginning of the class. This situation is consistent with the findings of Muhamad et al. (2018). They showed that the game approach improved the students' problem-solving skills, interests, and motivation to find a solution to the problem.

Regarding the challenge of insufficient teaching time and a lack of ICT infrastructure, modular approaches such as flipped classrooms have been used to encourage students to learn in a situation that focuses on self-development (UNESCO, 2020). In this study, the participants used instructional videos with related content, clear instructions, and worksheets as part of the Google classroom learning platform. The students can follow the instructions to engage in revision or self-paced learning in their spare time. This modular approach has ensured that teachers can deliver mathematical content and increase the effectiveness of learning a skill (Alias et al., 2020). For students with unstable internet connections, the participants have used a modular approach to ensure that the students continue learning and send work through other channels such as WhatsApp, by email, or as a hand-in hardcopy. In short, an appropriate teaching approach needs to be planned and implemented by the mathematics teachers to help students master sentence-based mathematics problem-solving skills.

6. Conclusion

Overall, this study has expanded the literature related to the challenges when teaching sentence-based mathematics problem-solving skills and the approaches that can be applied while teaching to overcome the challenges faced. This study has shown that students have difficulty mastering sentence-based mathematics problem-solving skills because they do not achieve the minimum mastery of factual knowledge, procedural skills, conceptual understanding, and the ability to choose appropriate strategies (Collins and Stevens, 1983). This situation needs to be taken into account because sentence-based mathematics problem-solving skills train the students to always be prepared to deal with problems that they will be faced with in their daily life. Through this study, teachers were found to play an essential role in overcoming the challenges faced by choosing the most appropriate teaching approach (Baul and Mahmud, 2021). An appropriate teaching approach can improve the students' sentence-based mathematics problem-solving skills (Wulandari et al., 2020). Teachers need to work hard to equip themselves with varied knowledge and skills to ensure that sentence-based mathematics problem-solving skills can be delivered to the students more effectively. Finally, the findings of this study were part of obtaining extensive data regarding the challenges that mathematics teachers face when teaching sentence-based mathematics problem-solving skills and the approaches used to address those challenges in the process of teaching mathematics. It is suggested that a quantitative study be conducted to find out whether the findings obtained can be generalized to other populations. This is because this study is a qualitative one, and the findings of this study cannot be generalized to other populations.

The findings of this study can be used as a reference to develop the professionalism of mathematics teachers when teaching mathematical problem-solving skills. However, the study's findings, due to being formulated from a small sample size, cannot be generalized to all mathematics teachers in Malaysia. Further studies are proposed to involve more respondents to better understand the different challenges and approaches used when teaching sentence-based mathematics problem-solving skills.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This study was reviewed and approved by The Malaysian Ministry of Education. The participants provided their written informed consent to participate in this study.

Author contributions

AL conceived and designed the study, collected and organized the database, and performed the analysis. AL and MM co-wrote the manuscript and contributed to manuscript revision. All authors read and approved the final submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Can impoverished family nurture rich sons any more? The effect of household income on intergenerational transmission of education: Evidence from China

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Family investment in education is an important variable influencing the educational attainment of children. Family investment in education is influenced by family income, and the increase in family income gap will aggravate the inequity of education and enhance the degree of intergenerational transmission of education. But the above theories need to be further tested in reality. This paper uses the 2018 China Family Panel Studies (CFPS) to verify the role of Chinese family income on intergenerational transmission of education through the education transition matrix and the mediating effect model, and examines the effect of college expansion policy on the mediating effect of family income on intergenerational transmission of education. The results show that: (1) The education level of parents has obvious transmissibility to the education level of children. The solidification rate of intergenerational transmission of education between parents and children is 25.72%, the upward mobility rate is 60.58% and the downward mobility rate is 13.70%. (2) The mediating effect model shows that the total effect of the parents' education level on children's education level is 0.279 and the direct effect is 0.272, and the family income plays a mediating effect in the intergenerational transmission of education, and the mediating degree reaches about 2.6%. (3) The expansion of higher education provides more opportunities for children of society, especially lower-middle-income families, to receive higher education, which weakens the mediating effect of family income in the intergenerational transmission of education. The findings of this paper provide support for policymakers to increase public investment in education.

KEYWORDS

intergenerational transmission of education, household income, transmission matrix, intermediary effect, China

1. Introduction

Since the implementation of the reform and opening-up policy in 1978, China has experienced rapid economic growth, but at the same time, the income gap among residents has been widening. One solution to the problem of how to narrow the income gap among residents is to promote equalization of education. Education, as a key production factor of human capital (An, 2005), plays an important role in the future development of individuals as well as in enhancing family income (Becker and Nigel, 1986). Educational functionalism argues that higher levels of education can help educated people acquire higher skills, thus enhancing intergenerational class mobility (Schneewind, 2015; Gul et al., 2020); conflict theory, on the other hand, believes that education is mainly a tool for social class reproduction and an intermediary medium for parents to pass social resources to their offspring (Bercovitch et al., 2009). In recent years, with the continuous expansion of education in China, the education level of the residents has been significantly improved, but there is also a gradual phenomenon of class solidification (Tadesse et al., 2022), and "it is difficult to produce noble children from a poor family" has been hotly debated in the society. This phenomenon reflects the importance people attach to social class solidification, and also reflects people's concern about the intergenerational transmission of education. Intergenerational transmission of education is a form of intergenerational transmission, which means that the education level of parents has an impact on the education level of their children. Stronger intergenerational transmission of education means lower intergenerational mobility, and children of highly educated parents also have high education, which further contributes to class solidification and thus educational inequality; while weaker intergenerational transmission of education means stronger intergenerational mobility. When the intergenerational transmission of education is weaker, education will be more equal, the view of "reading changes fate" will be more recognized, and class mobility will be stronger.

There has been very extensive research on the intergenerational transmission effect of education, and most scholars believe that the intergenerational transmission effect of education exists (Sewell and Hauser, 1993; Chevalier et al., 2003). The educational level of parents can effectively explain the educational level of their children, and when parents have a high level of education, they are more likely to raise children with a high level of education (Haveman and Wolfe, 1995; Yang and Wan, 2015; Huo and Golley, 2022), and the educational level of children during their growth process depends to a large extent on the educational level of their parents (Kwenda et al., 2015). Treiman (1997) found that the number of years of education of parents had a positive effect on the number of years of education of the offspring, as shown by the fact that when the number of years of education of the parent increased by 1 year, the number of years of education of his children increased by half a year. Some studies have shown that the intergenerational transmission of educational attainment from parents to their offspring is strong in China (Li and Zhou, 2018; Dong et al., 2020), and that parents' educational attainment has a greater impact on their children's academic achievement; the longer the number of years of education of parents, the longer the number of years of education of their children (Qiu and Xiao, 2011; Wang et al., 2016; Fang and Feng, 2018). Based on CGSS data, Li and Huang (2020) conducted an empirical study on the current situation of intergenerational mobility in education in China using the probability transition matrix and intergenerational elasticity, and found that the educational attainment of Chinese parents positively contributes to the educational attainment of their children, with significant intergenerational transferability of education. Hiroshi and Li (2008) also concluded that parents' education level has a highly significant positive effect on the education level of their offspring. Li (2003) found that children of parents with education level of high school and above will have relatively 2.3 years more years of education relative to parents with education level of high school and below; children of fathers with education level of junior high school and above will have 1 year more years of education compared to fathers with education level of illiterate/semi-literate. Sun and Yan (2015) found that parents' education level positively influenced their children's education level; specifically, children of fathers with high education levels were more likely to receive higher education, and mothers' education level had a greater impact on their children's education in junior high and high school (Zhou and Cheng, 2016).

Family income is a factor that directly affects the intergenerational transmission of education (Hanushek, 1986; Daviskean, 2005). Haveman and Wolfe (1995) found a significant effect of family income on the educational attainment of offspring. Brooks-Gunn and Duncan (1997) selected family socioeconomic status as a core variable and found that parental education and family socioeconomic status all had a significant effect on children's educational attainment, with children from high-income families being more likely to receive higher education. Compared to parents who are not well educated, parents who are well educated can obtain higher social status and family income, and they pay more attention to their children's education and are willing and able to invest more money and other resources to give their children more educational advantages (Yao et al., 2006; Ma and Wang, 2015; Wu and Huang, 2016; Wiedner and Schaeffer, 2020). With the development of China's economy and society, the influence of family income and family conditions on individuals' educational attainment gradually increased (Pang et al., 2013; Wang and Shi, 2014; Liu et al., 2015; Li and Zheng, 2017; Zou and Ma, 2019). As China's social stratification intensified after 1992, the influence of family class background began to emerge, with higher-income families having more resources, an advantage that was reflected in the educational opportunities of the next generation (Wei et al., 2019). Using data from a national sample survey, Li (2003) found that household economic status has an increasing effect on children's education, and that annual household income at age 14 has a significant effect on educational attainment for those in rural areas and for female students, but not for those in urban areas and for male students. A more precise study of her showed that children of fathers earning more than $2,000 per month had a higher chance of enrolling in undergraduate or professional education (Li, 2010). Hiroshi and Li (2008) analyzed regional differences in the intergenerational transmission of education and found that children of landowning or wealthy peasant families received relatively higher levels of education.

Relevant studies have shown that in the case of unequal distribution of educational resources, the influence of family income on individual educational attainment gradually increases (Huang, 2013), usually manifesting in the lower educational attainment of rural children compared to urban children, with significant differences between urban and rural areas. Despite the disparity in students' family conditions and innate abilities, the schooling process should provide the fairest possible opportunity for each child. Then, in response to the phenomenon of educational inequality, how to effectively and rationally achieve resource allocation and promote educational equity is the focus of future research. This study investigates the effect of family income on intergenerational transmission of education using China Family Panel Studies (CFPS) data, and on this basis, we explore whether the policy of college expansion can attenuate this effect and provide a reference to alleviate the problem of unequal access to educational resources for disadvantaged families in China.

2. Data and method

2.1. Data source and description

The data are from China Family Panel Studies (CFPS), funded by Peking University and the National Natural Science Foundation of China. The CFPS is maintained by the Institute of Social Science Survey of Peking University. CFPS reflects social, economic, demographic, educational, and health changes in China by tracking and collecting data at the individual, household, and community levels. The CFPS is a nationwide, large-scale, multidisciplinary social tracking survey project that focuses on the economic and non-economic well-being of Chinese residents, as well as many research topics including economic activities, educational outcomes, family relationships and family dynamics, population migration, health, etc. The CFPS uses implicitly stratified, systematic probability sampling proportional to population size, and targets household households in 25 provinces of China and the sample of all household members in the family households. In the empirical analysis part of the study, this paper uses the household member relationship database, household economic database, child proxy database, and individual self-response database from the CFPS2018. Considering the intergenerational transmission of education as the influence of the educational level of the paternal members in a household on the educational level of their offspring, this paper selects the data of adults who have completed high school from the household member relationship pool to create an observation sample with the offspring as the basis.

The core variables in this paper include household income, and educational attainment of the parent and offspring. (1) Household income. In this paper, the net income of all households is selected as the measure of household income. (2) Education level. The educational level of parents is expressed by the highest education of father and mother as the educational level of parents, and the educational level of children is measured by the highest education of children. For the eight categories of "illiterate/semi-literate, elementary school, junior high school, high school (junior college/technical school/vocational high school), college, bachelor's degree, master's degree, and doctorate," the corresponding years of education are 1, 6, 9, 12, 15, 16, 19, and 22 years, respectively. (3) The control variables selected in this article include intelligence level, health status, gender of children, number of family members, urban and rural population classification, and province of affiliation. The descriptive statistics of the variables selected in the article are shown in Table 1.

Table 1 demonstrates the mean, standard deviation, minimum and maximum values of the main variables in this paper, from which it can be seen that the average years of education of the offspring are 10.95 years, which basically reaches the high school level, and the years of education of the parents is 8.32 years. It indicates that with the socio-economic development, China pays more and more attention to education, the education level of the offspring has significant increase compared to their parents' generation, and the offspring are getting more and more opportunities to receive education. As far as the data of other control variables are concerned, among the total sample of children, the percentage of males is 54.02% and the percentage of females is 45.98%, and in terms of urban–rural classification, the percentage of rural population is 56.48% and the percentage of urban population is 43.52%.

TABLE 1 Descriptive statistics of the sample.

Variable	Label	Obs	Mean	Std. Dev.	Min	Max
Parent_edu	Highest education of parents	5,039	2.86	1.09	1.00	7.00
ParenteduY	The maximum length of schooling of parents	5,039	8.32	3.57	1.00	19.00
Child_edu	Highest education of child	5,039	3.75	1.27	1.00	8.00
ChildeduY	The maximum length of schooling of child	5,039	10.95	3.57	1.00	22.00
Family size	Number of family members	5,039	4.36	1.92	1.00	16.00
Fincome	Family net income	5,039	9.14	16.12	0.00	506.50
Urban	Urban and rural classification based on China National Bureau of Statistics	5,012	0.44	0.50	0.00	1.00
Province	Chinese provinces	5,030	39.74	15.38	11.00	65.00
Health	level of health	3,622	5.47	1.28	1.00	7.00
Intelligence	Intelligence level	4,196	4.92	1.40	1.00	7.00

2.2. Method

(1) Switching matrix. The transition matrix, also known as the transfer probability matrix, is mainly used to study the mobility of income, the transition matrix provides us with the possibility to observe the flow of economic output at any point and is complementary to the intergenerational regression coefficient and the correlation coefficient. For the income dimension, the transition matrix can be measured using different income classes, in the general sense of a double random matrix of the following form (Cao and Liu, 2018).

$$P(x,y) = p_{ij}(x,y) \in R_+^{m \times m} \tag{1}$$

Where $p_{ij}(x,y)$ represents the probability of an individual shifting from income level i in period t to income level j in period $t+1$. m is the number of rankings from lowest to highest by income level, which can be set by the analyst at any level as needed. All element values of this matrix are probabilities, so it takes values between 0 and 1; it is a doubly stochastic matrix, where larger elements on its main diagonal mean that individuals who were at a certain income level in the previous period are more likely to remain at the same income level in the current period, and therefore have less intergenerational income mobility (Formby et al., 2004). Similar to the income mobility matrix, the education transition matrix divides both the educational level of the parent and the educational level of the offspring into levels, with each row indicating the educational level of the offspring, each column indicating the educational level of the parent, and the numbers intersecting the rows and columns indicating the probability of their offspring entering each stage of education when the educational level of the parent is at that level (Li, 2018). Based on the intergenerational income conversion matrix established by Zhou and Zhang (2015), Ji and Liang (2020), and Xu and Mei (2021), this study introduces it into the intergenerational education conversion matrix study and constructs the following conversion matrix.

$$P = \begin{vmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} \\ p_{21} & p_{22} & p_{23} & p_{24} & p_{25} \\ p_{31} & p_{32} & p_{33} & p_{34} & p_{35} \\ p_{41} & p_{42} & p_{43} & p_{44} & p_{45} \\ p_{51} & p_{52} & p_{53} & p_{54} & p_{55} \end{vmatrix} \ldots \quad (2)$$

Each probability p_{ij} in equation (2) represents the probability of a child acquiring education level *j* when the parent's education level is at level *i*. The direction of intergenerational mobility can also be seen when observing the magnitude of intergenerational mobility in education. In this paper, three main mobility indicators are calculated based on the transformation matrix: the solidification rate (*SR*), the upward mobility rate (*UR*) and the downward mobility rate (*DR*), as shown in Equation (3) to Equation (5). The solidification rate indicates the non-mobility ratio, which is the probability that the parent and the child are at the same educational level; the upward mobility rate indicates the probability that the child's educational level is higher than the parent's educational level; and the downward mobility rate indicates the probability that the child's educational level is lower than the parent's educational level. The downward mobility rate and upward mobility rate mainly reflect the direction of intergenerational mobility (Gu, 2012).

$$SR = \sum_{i=j} a_{ij} / \sum a_{ij} \quad (3)$$

$$UR = \sum_{i>j} a_{ij} / \sum a_{ij} \quad (4)$$

$$DR = \sum_{i<j} a_{ij} / \sum a_{ij} \quad (5)$$

There are two main ways to build the mediating effect econometric model, one is to test the core variable coefficient to the mediating variable *a* and the mediating variable coefficient to the explained variable *b* sequentially, such as the sequential test coefficient method, and the other is to test the product of *a* and *b*, such as the Sobel test and Bootstrap test, etc. Since the derivation of the test statistic of the Sobel method requires the assumption that $\widehat{ab}$ obeys a normal distribution, even if each of these coefficients is normally distributed, its product is usually not normal, thus the calculation of the standard error S_{ab} above is only an approximation and may be inaccurate. Therefore, referring to the research method of Wen and Ye (2014), we try to use the one-time test coefficient method and Bootstrap test method for empirical testing, and the specific model is established as follows.

$$Y = cX + w_1 \quad (6)$$

$$M = aX + w_2 \quad (7)$$

$$Y = c'X + bM + w_3 \ldots \quad (8)$$

Coefficient *c* in equation (6) indicates the total effect of the explanatory variable *X* on the explanatory variable *Y*. Coefficient *a* in equation (7) indicates the regression coefficient of the explanatory variable *X* on the mediating variable *M*. Coefficient c' in equation (8) indicates the direct effect of the independent variable *X* on the dependent variable *Y* after controlling for the effect of the mediating variable *M*, and coefficient *b* is the effect of the mediating variable *M* on the dependent variable *Y* after controlling for the effect of the independent variable *X*. According to the test procedure of Wen and Ye (2014), the sequential regression test is conducted: firstly, the coefficient *c* of equation (6) is tested to make the explanatory variable regress on the explained variable; secondly, the coefficient *a* of equation (7) is tested to make the explanatory variable regress on the mediating variable; thirdly, the coefficient *b* of equation (8) is tested to make the explanatory and mediating variables regress on the explained variable at the same time. If the coefficient *c* is significant and both coefficients *a* and *b* are significant, the mediating effect is significant. Regarding the stepwise method of Baron and Kenny (1986), the first step tests the total effect of *X* on *Y*; the second step actually tests the significance of the product of the coefficients, indirectly by sequentially testing the coefficients *a* and *b*; and the third test is used to distinguish between full or partial mediation.

3. Results

3.1. Intergenerational transmission of education

Table 2 shows the overall transition between paternal and offspring education, from which it is clear that there is a positive relationship between parents' education level and children's education level. When parents' education level is illiterate/semi-literate, the probability of children's education level being high school or above is 24.85%, and the probability of children's education level being university undergraduate or above is 3.49%; when parents' education level is elementary school, the probability of children's education level being high school or above is 42.43%, and the probability of children's education level being university undergraduate or above is 6.24%; when parents' highest education level is high school, the probability of children's education level being high school or above is 69.38%, and the probability of children's education level being university undergraduate or above is 6.24%. When the parent's highest education is a bachelor's degree, the probability that the child's education is high school or higher is 85% and the probability that the child has a bachelor's degree or

TABLE 2 Education intergenerational transmission transition matrix.

Highest parental education	Probability of children receiving the highest degree (%)							
	Illiterate / semi-literate	Primary school	Junior high school	Senior high school	College	Undergr-aduate	Master	PhD
Illiterate / semi-literate	11.42	21.55	42.17	16.76	4.60	3.13	0.18	0.18
Primary school	4.32	16.65	36.59	26.10	10.09	6.16	0.08	0.00
Junior high school	1.43	7.50	32.54	33.28	15.24	9.47	0.49	0.05
Senior high school	1.52	4.00	25.11	32.36	14.94	20.35	1.73	0.00
College	1.56	1.56	12.50	42.19	16.15	22.92	3.13	0.00
Undergraduate	1.00	1.00	13.00	37.00	8.00	34.00	6.00	0.00
Master	0.00	0.00	0.00	0.00	0.00	33.33	66.67	0.00

TABLE 3 Distribution of children's education under different family income.

Family village income quantile	Probability of children receiving the highest degree (%)							
	Illiterate / semi-literate	Primary school	Junior high school	Senior high school	College	Undergr-aduate	Master	PhD
0–20%	6.04	18.00	38.56	24.74	8.13	4.30	0.12	0.12
20–40%	3.91	12.08	36.23	29.19	10.25	7.73	0.52	0.09
40–60%	3.08	9.52	32.24	31.35	14.38	8.83	0.60	0.00
60–80%	2.47	6.53	31.75	32.44	13.95	11.97	0.89	0.00
80–100%	0.99	6.15	21.83	31.35	16.17	21.53	1.98	0.00

higher is 40%. The solidification rate of intergenerational transmission of education between the father's and children's generations is 25.72%, upward mobility is 60.58% and downward mobility is 13.70%. The probability of upward mobility of children's education is very high. It can be seen that if both parents' educational attainment is at a low level, their children's educational attainment is also low, and the probability of obtaining a university degree or above is very low, and when parents' educational attainment increases, the probability of children's educational attainment increasing increases, and when parents' educational attainment is university or above, the probability of children's educational attainment at junior high school or below is very low.

3.2. Children's education in different family income classes

To investigate the relationship between family economic status and children's educational attainment, family income quintiles are now divided and the samples within their quintiles represent families in five income classes: low-income families (0–20%), lower-middle-income families (20–40%), middle-income families (40–60%), upper-middle-income families (60–80%), and high-income families (80–100%). The household income profile and children's education were linked to obtain Table 3.

Table 3 shows that the higher the household income, the higher the educational attainment of the children of the household, especially the frequency of receiving education above bachelor's degree will increase. The lower the family income, the lower the educational level of their children, especially the frequency of receiving education below junior high school will increase. Specifically, when the family income is in the low-income class, the frequency of their children's education level being junior high school or below is 62.6%, the probability of being a bachelor's degree or above is 4.54%, and the frequency of the children's education level of low-income families is the largest being junior high school, 38.56%; when the family income is in the middle-income class, the probability of their children's education level being junior high school or below is 44.84%, and the probability that they have a bachelor's degree or above is 9.43%. When the household income is in the higher income bracket, the probability of having children with education level of junior high school or below is only 28.97%, and the probability of having children with university degree or above is 23.51%. This shows that the higher the family income level, the more likely their children will receive a higher level of education, especially higher quality education represented by a bachelor's degree. For low-income families, the frequency of their children receiving undergraduate education is 4.30%, and for high-income families, this frequency rises to 21.53%, which is five times higher than for low-income families.

3.3. Mediating effects of household income on intergenerational transmission of education

Table 4 presents the results of the mediating effect of family income on the intergenerational transmission of education, with the regression

TABLE 4 Results of the mediating effect of household income on the intergenerational transmission of education.

Variable	Model 1	Model 1	Model 3
	ChildeduY	Fincome	ChildeduY
ParenteduY	0.279***	0.722***	0.272***
	(0.016)	(0.084)	(0.016)
Fincome			0.010***
			(0.003)
Health	−0.074	0.808***	−0.083
	(0.052)	(0.275)	(0.052)
Intelligence	0.173***	−0.583**	0.179***
	(0.049)	(0.259)	(0.049)
Family size	−0.159***	1.052***	−0.170***
	(0.029)	(0.154)	(0.029)
Intercept	8.965***	−1.234	8.978***
	(1.168)	(6.159)	(1.167)
Gender	YES	YES	YES
Province	YES	YES	YES
Urban	YES	YES	YES
Number of obs	3,610	3,610	3,610
R^2	0.192	0.102	0.195
Adj_R^2	0.185	0.094	0.187
F	27.470	13.050	26.980

"*," "**," and "***" indicate that they are significant at the 10, 5, and 1% levels in turn, and are not significant if they are not marked. The numbers in parentheses in the table are standard errors.

coefficients and robust standard errors for each variable separately. In Table 4, Model 1 is the total effect of the effect of paternal education on the educational attainment of the offspring when no mediating variables are included, and the results show that at the 1% confidence level, paternal education has a significant positive effect on the educational attainment of the offspring, and a 1-year increase in paternal education is associated with a 0.279-year increase in the educational attainment of the offspring. The explanatory variable in model 2 is household income and the explanatory variable is paternal educational attainment, and the results show that at the 1% confidence level, a 1-year increase in paternal educational attainment increases household income by 7,220 CNY. This indicates that the educational attainment of the father's generation has a positive effect on household income. Model 3 shows the results of the direct effect of paternal educational attainment on offspring's educational attainment after the inclusion of the mediating variable, household income. Model 3 shows that at the 1% confidence level, paternal education still has a positive effect on offspring's educational attainment, with an estimated coefficient of 0.272. The independent and mediating variables in models 1, 2, and 3 are significant, indicating a significant mediating effect. The effect of paternal education on offspring's educational attainment was reduced by 0.007 with the inclusion of mediating variables, indicating that paternal education influences household income, which in turn has an effect on offspring's educational attainment. Family income as a mediating variable explains 2.6% of the medium effect of paternal education on offspring's educational attainment. Further testing of the model with Sobel-Goodman Mediation Tests revealed that all coefficients passed the test at the 1% significance level, providing further support for the mediating role of family income in the intergenerational transmission of education.

4. Discussion

4.1. Robustness test

The Bootstrap method is a method of repeatedly sampling from a sample, provided that the sample is representative of the total. The Bootstrap method is also a direct test of the hypothesis H0: $ab = 0$. In this paper, the Bootstrap method is used to randomly sample 2000 times to test the robustness of the mediating effect of family financial investment in education between family income and children's cognitive ability. The specific procedure is as follows: firstly, the original sample is repeatedly sampled 2000 times with put-backs to obtain 2000 Bootstrap samples; secondly, the estimates of the 2000 Bootstrap samples $\widehat{ab}$ are obtained, and the whole estimates are expressed as $\{\widehat{ab}\}$ ($\widehat{ab}$ is ordered by size), and the 2.5th percentile and 97.5th percentile of $\{\widehat{ab}\}$ constitute the confidence level of ab is the 95% confidence interval; thirdly, if the confidence interval does not contain 0, then ab is significantly not equal to 0 and passes the mediating effect test. The results are shown in Table 5.

According to Table 5, the indirect effect of family income in the intergenerational transmission of education is 0.007, and the confidence interval of Bootstrap's bias correction is [0.002, 0.015], this confidence interval does not include 0. This result indicates that the mediating role of family income in the intergenerational transmission of education holds, specifically, a 1-year increase in the parent's educational attainment can indirectly increase the offspring's education level by 0.007 years through the family income. Overall, the results of both the stepwise and Bootstrap methods indicate that the mediating effect is robust. Specifically, the total effect of paternal education on offspring's education is 0.279, the direct effect is 0.272, and the mediating degree of family income is 2.6%. That is, 2.6% of the variation in offspring's educational attainment is explained by the variation in household income due to parents' educational attainment. This can indicate that higher education of parents has a positive effect on their household income and, in turn, higher education of their children.

To exclude the effect of variable selection on the model results, we re-estimated the mediating effect of household income on intergenerational transmission of education by replacing net household income with total household cash and savings (*deposit*) and total income of past respondents in the past 12 months (*fwage*) as mediating variables, respectively. The results of the resulting model are shown in Table 6.

According to Model 5, after using *deposit* as a mediating variable, the effect of parental education on offspring education decreases from 0.279 to 0.274, and the indirect effect is 0.006, which can explain about 2% of the total effect. According to Model 7, after using *fwage* as a mediating variable, the effect of paternal education on offspring education decreases from 0.279 to 0.256, and the indirect effect is 0.023, which can explain about 8% of the total effect. The results in Table 6 indicate that family income plays a significant mediating role in intergenerational educational transmission and that differences in family income are a non-negligible factor in differences in educational attainment.

4.2. Other influencing factors

It is generally accepted that an individual's educational achievement is influenced by three factors: individual giftedness, which is determined by genetic inheritance; family investment in education

TABLE 5 Results of the test for mediating effects based on Bootstrap method.

	Observed coefficient	Bias	Bootstrap std. err.	95% Confidence interval		Percentile/ bias-corrected
				Lower limit	Upper limit	
Indirect effect	0.007	0.001	0.004	0.002	0.017	Percentile
				0.002	0.015	Bias-corrected
Direct effect	0.272	−0.001	0.017	0.238	0.307	Percentile
				0.239	0.308	Bias-corrected
Total effect	0.279	0.000	0.017	0.246	0.314	Percentile
				0.246	0.315	Bias-corrected

TABLE 6 Results of the mediating effects model after replacing the main variables.

Variable	Model 4	Model 5	Model 6	Model 7
	Deposit	ChildeduY	fwage	ChildeduY
ParenteduY	0.514***	0.274***	0.415***	0.256***
	(0.075)	(0.016)	(0.031)	(0.016)
Deposit/ fwage		0.011***		0.056***
		(0.004)		(0.009)
Health	−0.044	−0.074	0.330***	−0.090*
	(0.244)	(0.052)	(0.102)	(0.052)
IQ	0.115	0.172***	−0.054	0.172***
	(0.230)	(0.049)	(0.095)	(0.049)
Family size	0.295**	−0.162***	0.686***	−0.191***
	(0.136)	(0.029)	(0.057)	(0.030)
Intercept	3.875	8.923***	3.068	8.789***
	(5.466)	(1.167)	(2.255)	(1.161)
Gender	YES	YES	YES	YES
Province	YES	YES	YES	YES
Urban	YES	YES	YES	YES
Number of obs	3,610	3,610	3,546	3,546
R^2	0.081	0.194	0.235	0.200
Adj_R²	0.090	0.187	0.228	0.193
F	11.38	26.96	34.77	27.44

"*," "**," and "***" indicate that they are significant at the 10, 5, and 1% levels in turn, and are not significant if they are not marked. The numbers in parentheses in the table are standard errors.

(Leibowitz, 1974), which is determined by family income and preferences for children; and public investment in education, which is determined by government spending on education (Becker and Nigel, 1979). This paper covers giftedness and family income in its model, but the effect of public education investment on the intergenerational transmission of education has not been discussed. Among the implemented policies, the expansion of colleges and universities in China is the most influential and widest-ranging policy. The following discussion focuses on the impact of the college expansion policy on the mediating effect of family income in the intergenerational transmission of education. Since the expansion of colleges and universities in China took place after 1999, it mainly affects the offspring born after 1981. In this paper, we divide the sample into two groups: those born before 1981 and those born after 1981, and analyze the impact of the college expansion policy by comparing them. The obtained results are shown in Table 7.

According to Model 8, the coefficient of the effect of paternal education on the offspring's education before the expansion of higher education is 0.297, and according to Model 10, the indirect effect of family income is 0.039, which explains about 13.2% of the effect of paternal education on the offspring's education. According to Model 11, after the expansion of colleges and universities, the coefficient of parental education on offspring's education is 0.274, and according to Model 13, the indirect effect of family income is 0.006, which explains about 2.2% of the effect of parental education on offspring's education, which is 11% lower than before the expansion of colleges and universities. In 1999, college enrollment increased by 513,200, reaching a total enrollment of 1,596,800, with a growth rate of 47.4%, and the expansion rate was 38.16% in 2000, 21.61% in 2001, and 19.46% in 2002. By 2003, the number of undergraduate and college students in China's general universities exceeded 10 million. With no significant increase in college tuition, the weakening effect of college expansion on family income in the intergenerational transmission of education is very obvious.

5. Conclusion

This paper selects relevant data from CFPS 2018 and examines the intergenerational transmission of education in China, the mediating effect of family income in the intergenerational transmission of education and the effect of college expansion on the mediating effect of family income in the intergenerational transmission of education through the transformation matrix as well as the test of mediating effect. Based on the previous empirical study, the main findings of this paper are as follows.

1. The educational attainment of parents has a significant transmission effect on the educational attainment of children, with a solidification rate of 25.72%, an upward mobility rate of 60.58% and a downward mobility rate of 13.70% for the intergenerational transmission of education between the father's and children's generations. When both parents' educational attainment is at a low level, the probability of their children obtaining a college degree or higher is very low, and when parents' educational attainment increases, their children's educational attainment will increase accordingly. The probability of children of parents who have received a college degree or higher education is significantly higher than that of others.

TABLE 7 Results of the mediating effect of college expansion on household income.

Variable	Model 8	Model 9	Model 10	Model 11	Model 12	Model 13
	ChildeduY	Fincome	ChildeduY	ChildeduY	Fincome	ChildeduY
ParenteduY	0.297***	1.593**	0.258***	0.274***	0.650***	0.268***
	0.077	0.622	0.079	0.016	0.084	0.017
Fincome			0.025*			0.009***
			0.013			0.003
Health	−0.064	1.510	−0.101	−0.073	0.622**	−0.079
	0.315	2.535	0.311	0.053	0.269	0.053
IQ	0.255	−1.670	0.296	0.169***	−0.399	0.173***
	0.304	2.450	0.300	0.050	0.254	0.050
Family size	−0.037	−0.794	−0.017	−0.159***	1.106***	−0.169***
	0.148	1.190	0.146	0.030	0.152	0.030
Intercept	9.723***	−10.488	9.983***	8.637***	−0.496	8.642***
	3.353	26.994	3.306	1.246	6.329	1.244
Gender	YES	YES	YES	YES	YES	YES
Province	YES	YES	YES	YES	YES	YES
Urban	YES	YES	YES	YES	YES	YES
Number of obs	126	126	126	3,484	3,484	3,484
R^2	0.479	0.515	0.500	0.191	0.106	0.192
Adj_R²	0.315	0.362	0.335	0.183	0.098	0.185
F	2.91	3.36	3.03	26.20	13.21	25.67

"*," "**," and "***" indicate that they are significant at the 10, 5, and 1% levels in turn, and are not significant if they are not marked. The numbers in parentheses in the table are standard errors.

2. The mediating effect model shows that the total effect of the parents' educational attainment on the offspring's educational attainment is 0.279 and the direct effect is 0.272, and the family income plays a mediating effect in the intergenerational transmission of education, with the degree of mediation reaching about 2.6%, that is, 2.6% of the difference in the offspring's educational attainment is explained by the difference in the family income caused by the parents' educational attainment, and it can be said that the higher the parents' educational attainment, the higher the positive effect on their family income. The higher the educational attainment of the parents, the higher the positive effect on their household income and, in turn, the higher the educational attainment of the children.
3. The expansion of colleges and universities provides more opportunities for children of society, especially those from lower and middle-income families, to receive higher education, weakening the mediating effect of family income in the intergenerational transmission of education. After the expansion of higher education, the mediating effect of family income in the intergenerational transmission of education decreases from 13.2 to 2.2%.

The limitation of this paper is that it does not further analyze the mechanism of the influence of family income on the intergenerational transmission of education. Future research can provide insight into the pathways of family income influence in the intergenerational transmission of education in terms of families' financial investment in education, parents' educational expectations, and parents' involvement in education. Compared with previous studies, the contribution of this paper is to empirically test the effect of household income on intergenerational transmission of education using a mediating effects model and to provide statistical evidence for this effect based on Chinese household surveys. The conclusions of this paper also provide guidance for policy makers to further strengthen public investment in education.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article.

Author contributions

XL: Conceptualization, methodology. WX: Supervision, review and editing. LW: writing–review and editing. TZ: analysis and discussions. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Measuring mathematics self-efficacy: Multitrait-multimethod comparison

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Previous studies had shown that there is a certain relationship between mathematics self-efficacy and math performance. For students, parents, and front-line scholars, it is urgent and important to study the measurement relationship between math achievement and self-efficacy. The research aimed to observe how to measure mathematics self-efficacy and find which of the three traits and which of the three methods better reflect individuals' self-efficacy. The present study used a multitrait-multimethod (MTMM) design to measure mathematics self-efficacy by constructing the confirmatory factor analysis (CFA) model. "Number and Algebra," "Graphics and Geometry," and "Synthesis and Practice" were considered three traits, and General-Math-Task-referenced self-efficacy, Unconventional-Math-Problem-referenced self-efficacy, and Motivated Strategies for Learning Questionnaire (MSLQ) self-efficacy were discussed as three methods to study. A questionnaire survey was used to obtain data. A total of 100 students completed all the questionnaires. Excel was used to collect math scores, and SPSS version 26.0 and AMOS version 26.0 were used to manage the data, confirm a hypothesis, and build a model by using MTMM design and CFA. CFA was used to verify convergent validity and discriminant validity. A total of eight models were constructed in the study that includes first-order CFA models and second-order CFA models, and model D was finally selected as the most perfect model in the second-order CFA model. The results showed that the "Synthesis and Practice" fields were the most significant reflection of self-efficacy among the three traits. MSLQ was the most significant reflection of self-efficacy among the three methods. It is beneficial to improve the level of self-efficacy from the aspect of mathematics subject. In addition, the research confirmed that CFA can support MTMM data for data modeling and found that the correlation between the Unconventional-Math-Problem-referenced self-efficacy and MSLQ is higher than that of General-Math-Task-referenced self-efficacy in the second-order model. It makes certain theoretical significance for improving students' mathematics self-efficacy levels.

KEYWORDS

self-efficacy, mathematics self-efficacy, multitrait-multimethod design, confirmatory factor analysis, academic performance in mathematics

1. Introduction

Bandura's social cognitive theory (Bandura, 1977) defined self-efficacy as people's view on how well he or she performs at specific assignments to reach a given level of performance. This shows how individuals, behaviors, and environmental aspects can influence one's actions. In general, the better self-efficacy the students have, the higher targets they aim for, the harder quests they seek, and the more unyielding with obstacles (Bandura, 1986). People tend to do the things they trust they can do well and resist those in that they do not have confidence in (Bandura, 1997). Therefore, how students view themselves has a great effect on their actions, and their belief that they can perform well can encourage them to make an effort at studying. Previous studies have suggested that the higher the self-efficacy, the more motivated and the better the academic performance of students (Pajares and Valiante, 1997). In the discipline of mathematics, mathematics self-efficacy refers to the evaluation of one's confidence to succeed in a math problem (Hackett and Betz, 1989). The Mathematics Self-Efficacy Scale was created by Betz and Hackett (1983). Theoretically, it is believed that individual mathematics self-efficacy can affect mathematics performance by influencing behavior and psychological process (Bandura, 1986; Bandura, 1997).

In empirical research, it is found that mathematics self-efficacy can accurately predict how well the outcomes are, by exploring the effect of mental ability and self-efficacy on math performance (Pajares and Kranzler, 1995). Mathematics self-efficacy uses both scores from lessons and exams to predict performance in math (Grigg et al., 2018). In math problem-solving, Pajares and Miller (1994) verified the function of self-efficacy in predicting and mediating. The results showed that self-efficacy is actually better at predicting their performance in solving problems than the other methods used to predict it. For measuring individuals' self-efficacy, Pajares and Miller (1995) proposed that this measure has to be strongly linked to the assignment being done; furthermore, it should show their confidence in succeeding at math problems and courses. According to Bandura (1997), as a key internal factor, self-efficacy refers to one's own view of his or her capability at performing tasks. Linnenbrink and Pintrich (2003) suggested that mathematics self-efficacy means opinions of abilities that can be expressed as "I think I can subtract numbers below 100". Animasaun and Abegunrin (2017) proposed that students with a low and medium level of mathematics self-efficacy may be subjected to either enactive mastery experiences (actual performances) or verbal persuasion in order to boost their self-efficacy. There exists a wide gap in home support, self-efficacy, active learning strategies, the attitude of students toward mathematics, and academic achievement between students with a weak, average, and strong interest in mathematics (Animasaun, 2021).

In measuring disciplinary self-efficacy, qualitative and quantitative methods were usually used at the same time. Dalgety and Coll (2006) used qualitative and quantitative data to observe changes in students' self-efficacy in the chemistry field. Webb-Williams (2018) investigated children's self-efficacy in science. Gao (2020) used a semi-structured interview using a "Q-sorting" process to investigate where mathematical self-efficacy came from in-depth. In contrast, some studies use quantitative methods only to measure disciplinary self-efficacy. Ding et al. (2022) tested the measurement invariance of mathematics self-concept and self-efficacy in the Programme for International Student Assessment (PISA) using multiple-group confirmatory factor analysis (CFA) and the alignment method. Through exploratory and confirmatory analyses and pilot testing, Luo et al. (2021) measured the self-efficacy of students in activities in STEM. Larsen and Jang (2021) used factor score path analysis on multiple levels to measure the relationship among mathematical achievement, instructional practices, and self-efficacy of students. Wong et al. (2021) determined the relationship between academic hardiness in science, learning science theory, and self-efficacy of students in studying science in Malaysian secondary schools, using the technology of modeling structural equations. In addition, Liu et al. (2020) described a link among task-specific and domain self-efficacy and math problem posing in detail using linear regression, generalized additive, and piecewise regression models. All these studies provide some references for the study of discipline self-efficacy.

Multitrait-multimethod (MTMM) modeling was shown as effective during the last 50 years of studies on psychology (Byrne, 2006). MTMM uses at least two methodologies to experiment with at least two traits. MTMM matrix can evaluate the effectiveness of convergence and divergence (Byrne, 2012; Kline, 2015). An effective and nice way to test the validity of a construct with MTMM is CFA in the structural equation model (SEM; Tildesley et al., 1995). Bong and Hocevar (2002) provided good use of MTMM in measuring self-efficacy. In their MTMM design, math, Korean, and English were discussed as three traits; Problem-referenced self-efficacy, Task-referenced self-efficacy, and Motivated Strategies for Learning Questionnaire (MSLQ) self-efficacy were considered three methods to measure self-efficacy. It is confirmed that factor analytic procedures of high order are useful to analyze the validity problems of convergent and discriminant.

How to calculate self-efficacy in math, especially using MTMM, which is so efficient and elegant as mentioned above? This study used an MTMM design to measure mathematics self-efficacy. "Number and Algebra," "Graphics and Geometry," and "Synthesis and Practice" were considered three traits, and General-Math-Task-referenced self-efficacy, Unconventional-Math-Problem-referenced self-efficacy, and MSLQ self-efficacy were discussed to be three methods. MSLQ self-efficacy was used to measure the cognitive level of academic events in the three fields and help students recognize the level of self-efficacy of learning motivation. This research aimed to explore how to measure mathematics self-efficacy and to find whether MTMM is a significant measurement of students' mathematics self-efficacy. The following studies were determined (1) to verify whether the MTMM can measure students' mathematics self-efficacy by establishing a high-order CFA model, (2) to find which of the three traits has more significant effects on students' mathematics self-efficacy through MTMM, and (3) to find which of the three methods has more significant effects on students' self-efficacy through MTMM.

2. Research methodology

2.1. Materials and methods

2.1.1. Participants and procedure

Due to the COVID-19 pandemic, the participants were only limited to two schools in Kaifeng and Shangqiu, Henan Province, China. Two rounds of tests were conducted and students of the autumn term in year 7 were selected as the research objects. In the round of prediction, 70 students were selected to test the quality of the test tools. The test tools were revised to have better validity according to the test results and expert opinions. During formal testing, 72 students from Kaifeng and 70 students from Shangqiu were selected for the offline test. General-Math-Task-referenced self-efficacy questionnaire, Unconventional-Math-Problem-referenced self-efficacy questionnaire, and MSLQ self-efficacy were distributed to teachers, who handed them out to students in the form of homework. Table 1 shows the number of questionnaires. Materials were collected online and offline, and 100 valid questionnaires were finally obtained for data analysis. The studies involving human participants were reviewed and approved by the Ethics Committee of Shandong Normal University. The participants provided their written informed consent to participate in this study.

2.2. Measurements

2.2.1. General-math-task-referenced self-efficacy questionnaire

In the "Mathematics Curriculum Standards for Compulsory Education (2011 Edition) (Ministry of Education of China, 2011)," mathematics learning was divided into four areas, namely, "Number and Algebra," "Graphics and Geometry," "Probability and Statistics," and "Synthesis and Practice." Among them, Synthesis and Practice is a comprehensive subject field based on the first three fields. Considering "Probability and Statistics" is much simpler than the others in junior high school, this study removed this field. Therefore, in this study, "Number and Algebra," "Graphics and Geometry," and "Synthesis and Practice" were included as three traits in the General-Math-Task-referenced self-efficacy questionnaire. For each trait, three questions were selected from relevant mathematical exercise questions in the seventh grade in the PEP edition, whose difficulty involves the following three levels: easy, medium, and difficult. For each question, different scores of self-efficacy were given due to different degrees of difficulty in question. For example, the second question of General-Math-Task-referenced self-efficacy in "Number and Algebra" is 5 marks in full. Finally, the experimenter asked the students to answer how confident he/she is to do this question on a scale of 0 to 5. The full score of self-efficacy for each question is shown in Table 2. This is the common process in verifying the belief of self-efficacy with given problems (Bandura, 1997).

2.2.2. Unconventional-math-Problem-referenced self-efficacy questionnaire

In light of the three traits, a total of 10 Unconventional-Math-Problem-referenced questions were selected that were similar to the cognitive level of seventh-grade students and had less correlation with the in-class learning content. According to the pre-test results, one question was deleted and three questions were kept in each trait. The Unconventional-Math-Problem-referenced self-efficacy questions are mostly open-ended questions that involve asking students to pose different levels of math problems or to pose and solve problems. Similar to the General-Math-Task-referenced self-efficacy questionnaire, different questions were given different total self-efficacy scores. For example, question 2 of Unconventional-Math-Problem-referenced self-efficacy in Graphics and Geometry is 8 marks in full. Then, the students assessed the degree of confidence in their solutions.

2.2.3. Motivated strategies for learning questionnaire self-efficacy

Bong and Hocevar (2002) introduced MSLQ self-efficacy, and it is used to measure self-efficacy, which is dedicated to measuring a certain field of mathematics subjects, and is a measure of the degree of recognition of statements of general academic events. It consists of the following six items: "I'm certain that I can understand what is taught in (a specific school subject) class," "I expect to do very well in (a subject) class," "I am sure that I can do an excellent job on the problems and tasks assigned for (a subject) class," "I know that I will be able to learn the material for (a subject) class," "My study skills are excellent in (a subject) class," and "I think I will receive a good grade in (subject) class." In light of "Number and Algebra," "Graphics and Geometry," and "Synthesis and Practice" in this article, 6 items were measured, respectively. Therefore, the questionnaire includes a total of 18 items. Response categories ranged from the 7-point Likert scale. The scores are shown in Table 2.

2.2.4. Numbers and scores of questionnaire questions

Details are summarized in Tables 1, 2.

2.3. Data analysis

Excel and SPSS version 26.0 were used for data statistics and collation, which aimed to analyze the Cronbach coefficient of each item and each facet, and "1" represents girls and "2" represents boys. Then, SPSS version 26.0 and Amos version 26.0 were used to analyze if these statistics were reliable and valid and calculate their model fit indexes. Amos was used to draw a model diagram based on data collected by SPSS, in which three traits and three methods affect each other. The final model diagram is shown in the following figure, in which reliability and validity, model fit, etc., were output.

TABLE 1 Numbers of questionnaire questions.

Methods Traits	General-Math-Task-referenced self-efficacy questionnaire	Unconventional-Math-Problem-referenced self-efficacy questionnaire	Motivated Strategies for Learning Questionnaire	Total numbers of questions
Number and Algebra	3	3	6	12
Graphics and Geometry	3	3	6	12
Synthesis and Practice	3	3	6	18
Total numbers of questions	9	9	18	36

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TABLE 2 Scores of each index of the questionnaires.

Methods	General-Math-Task-referenced self-efficacy questionnaire				Unconventional-Math-Problem-referenced self-efficacy questionnaire				Motivated Strategies for Learning Questionnaire							Total scores
Self-efficacy total score of each item / Traits	1	2	3	Total scores	1	2	3	Total scores	1	2	3	4	5	6	Total scores	
Number and Algebra	5	5	5	15	7	6	7	20	7	7	7	7	7	7	42	77
Graphics and Geometry	6	8	6	20	7	8	9	24	7	7	7	7	7	7	42	86
Synthesis and Practice	10	9	6	25	9	8	9	26	7	7	7	7	7	7	42	93
Total scores				60				70							126	256

The columns represent the traits, the methods represented by the rows, the number of questions indicated by the numbers in the first row, and the numbers in the following rows indicate the scores and total scores of the methods in a certain trait.

3. Analysis and discussion of results

3.1. Descriptive statistics of the model

According to the value of descriptive statistics, it was found that the values were almost significant of each trait, each method, and each item in the model. The table shows the reliability of the Cronbach coefficient, composite reliability, and convergent validity to test if the item and model are reliable and valid.

Table 3 shows indicators of factor loadings. Hair et al. (2009) deemed that loading estimates have to be more than 0.5, even more than 0.7 after standardizing. About the explanation of each factor loading of each trait in this article, for example, the factor loading of Unconventional-Math-Problem-referenced self-efficacy in Number and Algebra is 0.427, which represented the index of self-efficacy of Unconventional-Math-Problem-referenced self-efficacy in Number and Algebra is 0.427. That is to say, the index of self-efficacy of Unconventional-Math-Problem-referenced self-efficacy in Number and Algebra is increased by 1, and the value of Number and Algebra can increase by 0.427 in the whole model. The rest are the same as earlier. Through comparison, it can be found that the factor loadings of the three methods were basically acceptable, and the data were as follows: in Number and Algebra (Unconventional-Math-Problem-referenced self-efficacy = 0.427, General-Math-Task-referenced self-efficacy = 0.160, and MSLQ = 0.582), in Graphics and Geometry (Unconventional-Math-Problem-referenced self-efficacy = 0.581, General-Math-Task-referenced self-efficacy = 0.326, and MSLQ = 0.686), and in Synthesis and Practice (Unconventional-Math-Problem-referenced self-efficacy = 0.612, General-Math-Task-referenced self-efficacy = 0.398, and MSLQ = 0.707). Among them, "Synthesis and Practice" was the most important part of the three traits. Most of the factor loadings of the three traits were ideal in Unconventional-Math-Problem-referenced self-efficacy (Graphics and Geometry = 1.052, Number and Algebra = 0.895, and Synthesis and Practice = 1.186), in General-Math-Task-referenced self-efficacy (Graphics and Geometry = 0.640, Number and Algebra = 0.417, and Synthesis and Practice = 0.835), and in MSLQ (Graphics and Geometry = 0.954, Number and Algebra = 0.949, and Synthesis and Practice = 0.815). It was found that MSLQ has the greatest impact among the three methods.

Table 3 shows the factor loading of Graphics and Geometry, Number and Algebra, and Synthesis and Practice in the Unconventional-Math-Problem-referenced self-efficacy, General-Math-Task-referenced self-efficacy, and MSLQ. The factor loadings of Unconventional-Math-Problem-referenced self-efficacy in Number and Algebra were 0.691, 0.460, and 0.663, which indicated that they were basically acceptable. The factor loadings of General-Math-Task-referenced self-efficacy in Number and Algebra were 0.407, 0.175, and 0.921, which were basically acceptable. The factor loadings of MSLQ in Number and Algebra were 0.860, 0.602, 0.726, 0.769, 0.707, and 0.817, which were basically acceptable. The factor loadings of Unconventional-Math-Problem-referenced self-efficacy in Graphics and Geometry were 0.415, 0.739, and 0.616, which were mostly acceptable. The factor loadings of General-Math-Task-referenced self-efficacy in Graphics and Geometry were 0.089, 0.937, and 0.687, which were mostly acceptable. The factor loadings of MSLQ in Graphics and Geometry were 0.692, 0.460, 0.689, 0.687, 0.645, and 0.803, which were mostly acceptable. The factor loadings of Unconventional-Math-Problem-referenced self-efficacy in Synthesis and Practice were 0.432, 0.994, and 0.207, which indicated that they were basically acceptable. The factor loadings of General-Math-Task-referenced self-efficacy in Synthesis and Practice were 0.503, 1.050, and 0.609, which were within the acceptable range. The factor loadings of MSLQ in Synthesis and Practice were 0.654, 0.424, 0.694, 0.806, 0.675, and 0.769, which were mostly acceptable.

Table 3 presents the reliability and validity of the questionnaire. For reliability, two methods of Cronbach coefficient and composite reliability were used. The table shows that Cronbach coefficients of the Unconventional-Math-Problem-referenced self-efficacy questionnaire, the General-Math-Task-referenced self-efficacy questionnaire, and MSLQ were all close to 0.70, which was introduced by Nunnally and Bernstein (1994).

TABLE 3 Descriptive statistics of the model.

Facets	Questions	Unstd	S.E.	*T*-value	*p*	Std	*α*	CR	AVE
Alge	Pro	1				0.427	0.301	0.358	0.182
	Task	0.308	0.235	1.307	0.191	0.160			
	MSLQ	1.515	0.415	3.652	***	0.582			
Geo	Pro	1				0.581	0.457	0.549	0.305
	Task	0.088	0.112	0.784	0.433	0.326			
	MSLQ	1.466	0.428	3.421	***	0.686			
Prac	Pro	1				0.612	0.551	0.600	0.344
	Task	0.754	0.297	2.540	0.011	0.398			
	MSLQ	0.765	0.233	3.283	0.001	0.707			
Pro	Geo	1				1.052	0.821	1.033	1.105
	Alge	1.249	0.280	4.461	***	0.895			
	Prac	1.638	0.419	3.905	***	1.186			
Task	Geo	1				0.640	0.574	0.676	0.427
	Alge	4.589	5.085	0.902	0.367	0.417			
	Prac	14.406	15.044	0.958	0.338	0.835			
MSLQ	Geo	1				0.954	0.877	0.934	0.825
	Alge	1.421	0.226	6.275	***	0.949			
	Prac	0.874	0.173	5.047	***	0.815			
	AP1	1				0.691	0.607	0.638	0.376
Alge_Prob	AP2	0.321	0.107	3.007	0.003	0.460			
	AP3	0.944	0.317	2.975	0.003	0.663			
	AT1	1				0.407	0.432	0.536	0.348
Alge_Task	AT2	0.312	0.207	1.513	0.130	0.175			
	AT3	1.723	2.259	0.763	0.445	0.921			
	AQ1	1				0.860	0.884	0.885	0.565
	AQ2	0.636	0.100	6.378	***	0.602			
Alge_MSLQ	AQ3	0.789	0.097	8.172	***	0.726			
	AQ4	0.866	0.098	8.873	***	0.769			
	AQ5	0.788	0.100	7.871	***	0.707			
	AQ6	0.968	0.100	9.692	***	0.817			
	GP1	1				0.415	0.605	0.622	0.366
Geo_Prob	GP2	2.859	1.107	2.583	0.010	0.739			
	GP3	1.983	0.684	2.898	0.004	0.616			
	GT1	1				0.089	0.559	0.641	0.453
Geo_Task	GT2	20.821	33.959	0.613	0.540	0.937			
	GT3	10.88	13.051	0.834	0.404	0.687			
	GL1	1				0.692	0.826	0.827	0.450
	GL2	0.578	0.141	4.109	***	0.460			
Geo_MSLQ	GL3	1.020	0.171	5.957	***	0.689			
	GL4	1.039	0.175	5.943	***	0.687			
	GL5	0.969	0.172	5.624	***	0.645			
	GL6	1.232	0.184	6.698	***	0.803			
	PR1	1				0.432	0.430	0.599	0.406

(Continued)

TABLE 3 (Continued)

Facets	Questions	Unstd	S.E.	*T*-value	*p*	Std	*α*	CR	AVE
Prac_Prob	PR2	1.541	1.566	0.984	0.325	0.994			
	PR3	0.533	0.279	1.912	0.056	0.207			
	PT1	1				0.503	0.721	0.786	0.576
Prac_Task	PT2	1.996	0.557	3.581	***	1.050			
	PT3	0.716	0.148	4.842	***	0.609			
	PS1	1				0.654	0.829	0.834	0.465
	PS2	0.632	0.168	3.760	***	0.424			
Prac_MSLQ	PS3	1.154	0.200	5.775	***	0.694			
	PS4	1.22	0.190	6.436	***	0.806			
	PS5	1.02	0.180	5.652	***	0.675			
	PS6	1.299	0.208	6.245	***	0.769			

Alge, Number and Algebra; Geo, Graphics and Geometry; Prac, Synthesis and Practice; Pro, Unconventional-Math-Problem-referenced self-efficacy; Task, General-Math-Task-referenced self-efficacy; MSLQ, Motivated Strategies for Learning Questionnaire; Alge_Prob, Number and Algebra questions in Unconventional-Math-Problem-referenced self-efficacy questionnaire; Geo_Prob, Graphics and Geometry questions in Unconventional-Math-Problem-referenced self-efficacy questionnaire; Prac_Prob, Synthesis and Practice questions in Unconventional-Math-Problem-referenced self-efficacy questionnaire; ***$p < 0.001$.

The table shows how reliable each question, three methods, and three traits are. When talking about the CR value, Hair et al. (2009) thought that the rule of thumb for both calculations of reliability should be at least 0.7, which means reliable, and above 0.6, which is acceptable. Among the three traits, Graphics and Geometry (CR = 0.549) and Synthesis and Practice (CR = 0.600) had higher reliability than others, while Number and Algebra (CR = 0.358) had low reliability. The reliability of MSLQ (CR = 0.934) and General-Math-Task-referenced self-efficacy (CR = 0.676) was acceptable, while the reliability of Unconventional-Math-Problem-referenced self-efficacy (CR = 1.033) was the highest. In Number and Algebra, among the composite reliability of Unconventional-Math-Problem-referenced self-efficacy, General-Math-Task-referenced self-efficacy, and MSLQ, the reliability of Unconventional-Math-Problem-referenced self-efficacy (CR = 0.638) and General-Math-Task-referenced self-efficacy (CR = 0.536) was acceptable, and the reliability of MSLQ (CR = 0.885) was the highest among all questions. In Graphics and Geometry, among the composite reliability of Unconventional-Math-Problem-referenced self-efficacy, General-Math-Task-referenced self-efficacy, and MSLQ, the reliability of Unconventional-Math-Problem-referenced self-efficacy (CR = 0.622) and General-Math-Task-referenced self-efficacy (CR = 0.641) was acceptable, and the reliability of MSLQ (CR = 0.827) was the highest among all questions. In Synthesis and Practice, among the composite reliability of Unconventional-Math-Problem-referenced self-efficacy, General-Math-Task-referenced self-efficacy, and MSLQ, the reliability of Unconventional-Math-Problem-referenced self-efficacy (CR = 0.599) and General-Math-Task-referenced self-efficacy (CR = 0.786) was acceptable, and the reliability of MSLQ (CR = 0.834) was the highest among all questions.

If the average variance extracted (AVE) is at least 0.5, then this is a fitting rule of thumb with suitable convergence (Hair et al., 2009). Table 3 illustrates the convergent validity of three methods and three traits. Among the three traits, the validity of Graphics and Geometry (AVE = 0.305) and Synthesis and Practice (AVE = 0.344) was close to 0.5, and the validity of Number and Algebra (AVE = 0.182) was not high. Among the Unconventional-Math-Problem-referenced self-efficacy, General-Math-Task-referenced self-efficacy, and MSLQ, the validity of Unconventional-Math-Problem-referenced self-efficacy (AVE = 1.105) and MSLQ (AVE = 0.825) was both higher than 0.5, while the validity of General-Math-Task-referenced self-efficacy (AVE = 0.427) was not higher than 0.5. In Number and Algebra, the validity of Unconventional-Math-Problem-referenced self-efficacy (AVE = 0.376), General-Math-Task-referenced self-efficacy (AVE = 0.348), and MSLQ (AVE = 0.565) was close to 0.5. In Graphics and Geometry, the validity of Unconventional-Math-Problem-referenced self-efficacy (AVE = 0.366), General-Math-Task-referenced self-efficacy (AVE = 0.453), and MSLQ (AVE = 0.450) was close to 0.5. In Synthesis and Practice, the validity of Unconventional-Math-Problem-referenced self-efficacy (AVE = 0.406), General-Math-Task-referenced self-efficacy (AVE = 0.576), and MSLQ (AVE = 0.465) was close to 0.5. In general, the convergent validity of each method, each trait, and each item is good.

3.2. Goodness-of-fit indexes of the CFA model

Lai et al. (2010) proposed that we can compare the CFA of the first order and the second order by calculating the target coefficient to determine if it fits with statistics. The T value nearer one suggests that the second-order CFA is appropriate to substitute the first-order CFA, and the model is accurate. In this study, the second-order CFA model is appropriate to substitute the first-order CFA model.

This model fit indexes of the first-order CFA model and the higher-order CFA model are shown in Table 4. A total of eight models had been constructed in this study. Models 1 to 4 are the first-order SEM, and models A to D are the second-order SEMs. In models 1 and 2, the correlation of trait and method, respectively, cannot be found, and the fit indexes of the two models are not ideal. Model 3 is the first-order model in that traits and methods are not correlated, which is more acceptable than the model fit indexes of the first two models. Model 4 is the first-order model of 9 correlated methods and traits, which reflected the unique addition of a single method and single trait. Compared with the first three models, the model fit indexes of model 4 are better. Model A is the second-order model with three

TABLE 4 Goodness-of-fit indexes of confirmatory factor analysis model.

Model	Description	χ2/df	GFI	AGFI	TLI	CFI	RMSEA	SRMR
1	3 correlated method first-order factors only	1.809	0.645	0.599	0.678	0.698	0.090	0.090
2	3 correlated trait first-order factors only	2.191	0.554	0.497	0.527	0.556	0.110	0.120
3	3 correlated method and 3 correlated trait first-order factors with no trait-method correlation	1.677	0.675	0.608	0.731	0.764	0.083	–
4	9 correlated trait-method combination first-order factors	1.662	0.676	0.613	0.737	0.767	0.082	0.085
A	3 correlated method second-order factors	1.652	0.671	0.623	0.741	0.761	0.081	0.089
B	3 correlated trait second-order factors	1.835	0.650	0.600	0.668	0.694	0.092	0.113
C	3 correlated method and 3 correlated trait second-order factors with no trait-method correlation	1.651	0.673	0.618	0.741	0.766	0.081	–
D	Model C with Task method factor removed	1.645	0.675	0.624	0.744	0.766	0.081	0.090

correlated methods, model B is the second-order model with three correlated traits, and model C is the second-order model with three traits correlated with three methods; the method and traits are not correlated at the same time, standardized root mean square residual (SRMR) value cannot be estimated successfully, and model C had improved compared with the previous models. Model D is the second-order model based on model C except for General-Math-Task-referenced self-efficacy, and the value of SRMR could be estimated. Model D is the preset perfect model, and the model fit indexes were the best of all models.

A theory that a model illustrates reasonable fit when the change in data is less or equal to 3.0 was introduced (Kline, 2004): $\chi^2/df \leq 3$. Table 4 shows the value of all models which is less than or equal to 3, indicating that the fit indexes of all of them are reasonable.

In Table 4, the Adjusted Goodness-of-Fit Index (AGFI) and Goodness-of-Fit Index (GFI) figures in all models were between 0.5 and 0.7, close to the value which is generally accepted value of 0.90 (Hooper et al., 2008). With the model changing from second order to first order, it was found that the fit indexes of model D were better.

The comparative fit index ($CFI \geq 0.95$) is currently seen as illustrating goodness-of-fit (Hu and Bentler, 1999). CFI is an index of goodness-of-fit. The larger it is the better. It is a number between 0.0 and 1.0. Furthermore, it tries to set the level of freedom in the model straight into the calculation to adjust model complexity or parsimony (Iacobucci, 2009). Marsh et al. (2004) proposed that we should not criticize it when CFI is a bit below 0.95 or SRMR is a bit below 0.09. The CFI values of most models were between 0.7, which was close to the index of goodness-of-fit. With the model changing from the first order to the second order, it was found that model D's fit index was more fit than previous models.

The issue was tackled using the Non-Normed Fit Index (NNFI, also called Tucker–Lewis index), which prefers models that are simpler. However, when the samples are small, the value of NNFI could suggest bad fitness even though other data show fair fitness. The last issue about NNFI is that its non-normed characteristic figures could be higher than 1.0, therefore, making it difficult to analyze (Hooper et al., 2008). The indicators of each model were close to 0.8. On the whole, model D was closer to the standard indicators.

Root mean square error of approximation (RMSEA) values between 0.05 and 0.10 indicated good fitness, values higher than 0.10 indicated bad fitness, values between 0.08 and 0.10 indicated mediocre fitness, and values lower than 0.08 indicated nice fitness (MacCallum et al., 1996). All models' indicators in Table 5 were almost 0.08, which means that they were close to medium fit.

SRMR stands for "standardized root mean square residual," whose value is between 0.0 and 1.0. The value obtained by a well-fitted model is less than 0.05, but a value up to 0.08 is considered good enough (Hooper et al., 2008). The indicators of all models in Table 4 were considered to be around 0.08, which was acceptable.

3.3. Discriminant validity of each factor of the model

Pohl and Steyer (2012) proposed that if the analyzed trait can be distinguished from other traits, the discriminant validity is supported. If different measurement methods produce similar results when measuring the same trait, the convergent validity can be proven.

Table 5 shows the correlation coefficient of CFA in model 4. For example, the correlation coefficient of the Number and Algebra part in General-Math-Task-referenced self-efficacy was 0.590, which was above heterotrait-heteromethod (HTHM), heterotrait-homomethod (HThM), and homotrait-heteromethod (hTHM; Kenny, 2012)

TABLE 5 Correlation indexes of first-order confirmatory factor analysis model.

Factor	1	2	3	4	5	6	7	8	9
Alge_Task	**0.590**								
Prac_MSLQ	0.334	**0.682**							
Prac_Task	0.383	0.286	**0.759**						
Prac_Prob	0.379	0.398	0.441	**0.637**					
Alge_MSLQ	0.223	0.768	0.349	0.253	**0.752**				
Geo_MSLQ	0.148	0.768	0.318	0.341	0.909	**0.671**			
Geo_Task	0.057	0.259	0.506	0.644	0.233	0.186	**0.673**		
Geo_Prob	0.234	0.467	0.331	1.172	0.311	0.404	0.281	**0.605**	
Alge_Prob	0.002	0.229	0.235	0.967	0.202	0.268	0.267	0.991	**0.613**

Alge_Task, Number and Algebra part in General-Math-Task-referenced self-efficacy questionnaire; Prac_MSLQ, Synthesis and Practice part in Motivated Strategies for Learning Questionnaire; Geo_MSLQ, Graphics and Geometry part in Motivated Strategies for Learning Questionnaire.
For example, 0.590 represents the correlation of questions between "Number and Algebra" in General-Math-Task-referenced self-efficacy questionnaire, and other bold numbers represent the correlation of questions between trait in a certain method.

coefficients in the same row, indicating that the discriminant validity is good. The correlation coefficient of the Graphics and Geometry part in General-Math-Task-referenced self-efficacy was 0.673, which was higher than the coefficient of the same row or the same column, indicating that the discriminant validity is fine. The correlation coefficient of the Synthesis and Practice part in General-Math-Task-referenced self-efficacy was 0.759, which was higher than the coefficient of the same row or the same column, indicating that the discriminant validity is well.

The correlation coefficient of the Number and Algebra part in Unconventional-Math-Problem-referenced self-efficacy was 0.613, which was higher than the coefficient of the same row or the same column, indicating that the discriminant validity was average. The correlation coefficient of the Graphics and Geometry part in Unconventional-Math-Problem-referenced self-efficacy was 0.605, which was higher than the coefficient of the same row or the same column, indicating that the discriminant validity was general. The correlation coefficient of the Synthesis and Practice part in Unconventional-Math-Problem-referenced self-efficacy was 0.637, which was higher than the coefficient of the same row or the same column, indicating that the discriminant validity is general.

The correlation coefficient of the Number and Algebra part in MSLQ was 0.752, which was higher than the coefficient of the same row or the same column, indicating that the discriminant validity is general. The correlation coefficient of the Graphics and Geometry part in MSLQ was 0.671, which was higher than the coefficient of the same row or the same column, indicating that the discriminant validity is general. The correlation coefficient of the Synthesis and Practice part in MSLQ was 0.682, which is higher than the coefficient of the same row or the same column, indicating that the discriminant validity is general. In conclusion, the discriminant validity of the first-order model of CFA was acceptable.

To sum up, according to the research issue, we can measure individuals' mathematics self-efficacy by using MTMM and get the most appropriate model, as shown in Figure 1.

3.4. Discussion

This research found that individuals' mathematics self-efficacy can be measured by using MTMM and by constructing a high-order CFA model. In fact, certain psychological characteristics can be measured with MTMMs. Wang (2015) suggested using various ways of assessing and evaluating the multiple facets of metacognition and MTMM. Many researchers use the MTMM method as a measurement of psychological characteristics. Campbell et al. (2019) provided one example that considered using validating observation to comprehend how people teach in the university, with the use of modeling MTMM. Donaldson et al. (2020) examined two positive psychology structures using an MTMM research design. These studies had proved that MTMM is a professional psychological measurement method. Hidden variable models like CFA models and SEMs were proposed before 1990, to analyze the process of variability (Koch et al., 2017). Researchers do not agree on which parameterization of the CFA model characterizes MTMM data the most (Conway et al., 2004). At present, many studies support using CFA for MTTM figures. Conway et al. (2004) proposed that CFA supplies a most inclusive way of assessing MTMM figures. Nimlyat et al. (2018) proposed that other ways of assessing matrices of MTMM clearly favor using CFA. Kamakura and Ozer (2007) proposed that common matrixes in MTMM contain correlations between various traits calculated in various ways and let people assess how similar the ways are, i.e., convergence, and how unique they are, i.e., discrimination. A total of eight models were constructed in this study, which supported and verified the discriminant validity in the model of first-order CFA and the convergent validity of each facet. As indicated earlier, the present research attempts to find out whether MTMM data can measure mathematics self-efficacy by constructing a model of high-order CFA, so the study constructed the first-order CFA model and the second-order CFA model to measure mathematics self-efficacy, which indicated that CFA can support MTMM data for data modeling. The MTMM method provides a new idea and method for measuring mathematics self-efficacy.

According to the results, it was found that "Synthesis and Practice" had the most significant impact among the three traits, and MSLQ had the biggest impact on those three methods. "Synthesis and Practice" is a comprehensive field generated based on "Number and Algebra" and "Graphics and Geometry." The field of "Synthesis and Practice" applied the learned mathematics knowledge to specific life practices, which emphasize that mathematics knowledge originates from life and is applied to life, and helps students better understand knowledge at a certain level. In the present study, MSLQ is used to measure students'

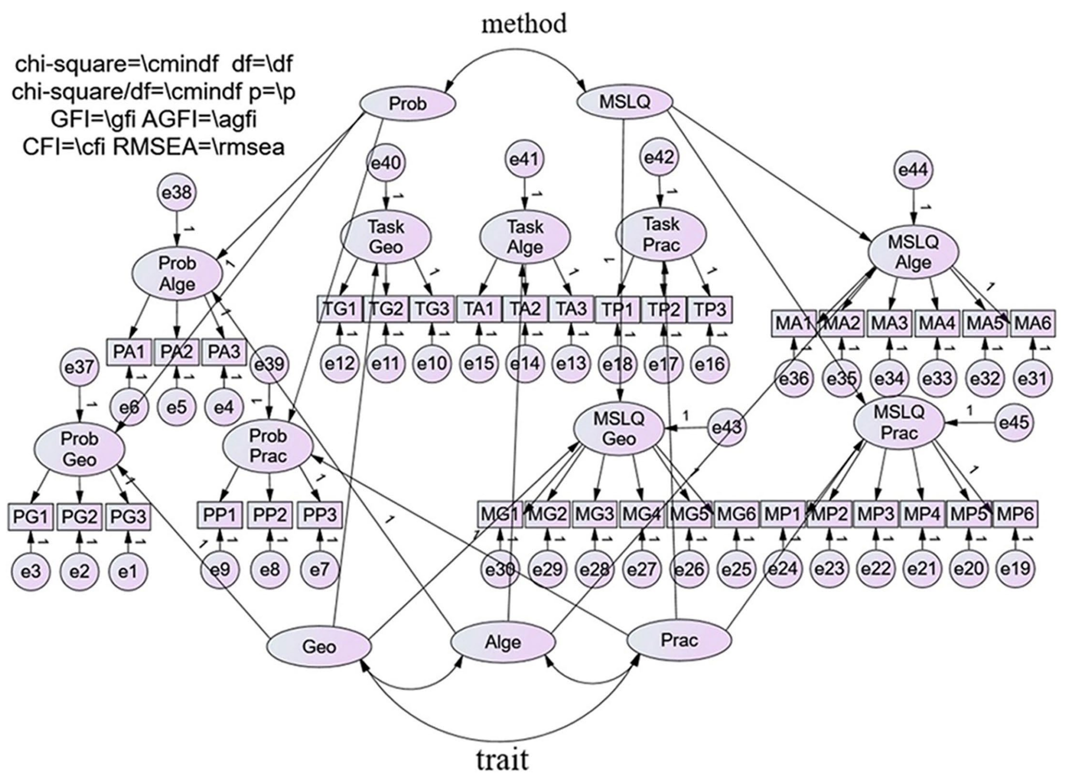

FIGURE 1
High-order confirmatory factor analysis model of multitrait-multimethod data with three correlated traits and two correlated method second-order factors with no trait–method correlation (model D). Prob, Unconventional-Math-Problem-referenced self-efficacy; MSLQ, Motivated Strategies for Learning Questionnaire; Geo, Graphics and Geometry self-efficacy; Alge, Number and Algebra self-efficacy; Prac, Synthesis and Practice self-efficacy.

recognition degree of “Number and Algebra,” “Graphics and Geometry,” and “Synthesis and Practice,” which is about academic events of mathematics knowledge. If the questionnaire is applied to specific classroom learning, it can give feedback on students’ achievements in time, help students improve their achievements, and improve students’ mathematical self-efficacy level.

Bong and Hocevar (2002) used two methods and three traits to measure self-efficacy by constructing models, which verified the effectiveness of the discriminant validity and convergent validity of the model of higher order CFA. This study used two methods and three traits to construct a high-order CFA model specifically for measuring math learning self-efficacy. When verifying the goodness-of-fit data of the second-order CFA model, it was found that the goodness-of-fit figures for those two methods of Unconventional-Math-Problem-referenced self-efficacy and MSLQ self-efficacy, and three traits were better in the second-order model, that is, the correlation between the Unconventional-Math-Problem-referenced self-efficacy and MSLQ is higher than that of General-Math-Task-referenced self-efficacy. Unconventional-Math-Problem-referenced self-efficacy involves problem-posing and problem-solving, including asking students to pose problems of varying levels and solve problems. Future research can use Unconventional-Math-Problem-referenced self-efficacy and MSLQ, which can use the MTMM method to measure students’ level of mathematics self-efficacy by constructing models. According to the evaluation results, educators could let students raise their self-efficacy in math through intervention in different areas of mathematics. The future research objects can be concentrated in the field of primary and secondary schools, but should not be limited to school age only. Objects with psychological traits that need to be measured can be much more. Future research can expand the scope of traits or methods, not only limited to three traits and three methods. Current research is calculating mathematics self-efficacy using the characteristics of the subject. The measurement field of future research can be transformed into the self-efficacy of a certain subject or the self-efficacy of the STEM field, and the self-efficacy can be improved using answers from research.

There are still some limitations in this study. First, seventh-grade students are chosen as the participants, and the representatives of the sample need to be improved. Second, this study only shows the degree of influence of certain traits and methods on mathematics learning self-efficacy; whether and how to use the research results to improve students’ academic performance in the future needs further research.

4. Conclusion

This research draws the following conclusions. (1) MTMM can measure mathematics self-efficacy by establishing a high-order CFA model. (2) Through the screening method of MTMM, the “Synthesis and Practice” field of the three traits can better reflect students’ self-efficacy. (3) Through the screening method of MTMM, among the three methods, MSLQ can better reflect the self-efficacy of students.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee of the Shandong Normal University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

WY contributed to the basic conception and design of the study. WY and SZ wrote the first draft of the manuscript and wrote sections of the manuscript, committed to the organization of the questionnaire, and contributed to the construction of the specific structure. SZ contributed to the collection of original data, data analysis, and model construction. YZ contributed to the revision of the thesis grammar. WY and YZ put forward some professional suggestions on the specific contents and parts of the manuscript. All authors contributed to the manuscript revision and read and approved the submitted version.

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Conflict of interest

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Supplementary material

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Development of associations between elementary school students' mindsets and attentional neural processing of feedback in an arithmetic task

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The aim of this study was to examine the development of the associations between elementary school students' mindsets and the attentional neural processing of positive and negative feedback in math. For this, we analyzed data collected twice from 100 Finnish elementary school students. During the autumn semesters of their 3rd and 4th grade, the participants' general intelligence mindset and math ability mindset were measured with a questionnaire, and their brain responses elicited by performance-relevant feedback were recorded during an arithmetic task. We found that students' fixed mindsets about general intelligence and math ability were associated with greater attention allocated to positive feedback as indicated by a larger P300. These associations were driven by the effects of mindsets on attention allocation to positive feedback in grade 4. Additionally, 4th graders' more fixed general intelligence mindset was marginally associated with greater attention allocated to negative feedback. In addition, the effects of both mindsets on attention allocation to feedback were marginally stronger when the children were older. The present results, although marginal in the case of negative feedback and mainly driven by effects in grade 4, are possibly a reflection of the greater self-relevance of feedback stimuli for students with a more fixed mindset. It is also possible that these findings reflect the fact that, in evaluative situations, mindset could influence stimulus processing in general. The marginal increase in the effects of mindsets as children mature may reflect the development of coherent mindset meaning systems during elementary school years.

KEYWORDS

mindset, P300 - event related potential, math, feedback, implicit beliefs

1. Introduction

Encountering feedback—information about one's performance or understanding—is part of students' daily experience in school. The effect of feedback on student outcomes, though, is far from homogeneous (Wisniewski et al., 2020) and seems, at least partly, to depend on individuals' beliefs about the malleability of their abilities (Hu et al., 2017). Mindsets—core beliefs about the malleability of human abilities—can be understood as meaning systems that perform an organizing function regarding the interpretation of one's experiences (e.g., receiving negative feedback about one's performance; Hong et al., 1999; Molden and Dweck, 2006). In line with this, mindsets have been associated with perceptions of negative feedback (Zingoni and Byron, 2017). The associations between students' mindsets and their perceptions of and reactions to feedback, errors, and failure experiences have been investigated using questionnaires (e.g., Zingoni and Byron, 2017), behavioral measures (e.g., Janssen et al., 2022), and also qualitative data from interviews (e.g., Limeri et al., 2020). Neuroscientific research provides the opportunity to gain a better understanding of mindset meaning systems by enabling the inspection of the neural processes associated with the perception and cognition of feedback, which is unattainable using behavioral measures or surveys. Nevertheless, such neuroscientific studies on mindsets are scarce. To our knowledge, there are two studies on the associations between mindset and automatic attention allocation to feedback (Mangels et al., 2006; Puusepp et al., 2021), both of them cross-sectional research. The tentative findings of these studies require replication. Furthermore, studies suggest that elementary school years are a period during which students' mindsets as meaning systems develop (Kinlaw and Kurtz-Costes, 2007; Gunderson et al., 2018), which highlights the importance of longitudinal studies among this age group. Therefore, the aim of the present study was to extend the previous research by investigating the development of the associations between mindsets and the attentional neural processing of feedback among elementary school students. More specifically, we focused on students' general intelligence and math ability mindsets and their attentional neural processing of positive and negative performance-relevant feedback in math in two consecutive school years.

Mindsets refer to core beliefs that people hold about the nature and malleability of certain human abilities and attributes, such as intelligence or personality (Dweck, 2000). These beliefs exist on a spectrum from a fixed mindset, believing that human abilities are unchangeable and fixed (entity theory), to a growth mindset, believing that these qualities and attributes are malleable and can be improved with effort and adaptive strategies (incremental theory; Dweck, 2000). Mindsets, while being mostly implicit, form an intricate meaning system that performs an organizing function regarding the interpretation of one's experiences and the planning of future behavior (Hong et al., 1999). The relevance of mindsets in educational contexts has been demonstrated among learners at various educational levels (Tempelaar et al., 2015; Gunderson et al., 2018; Bostwick et al., 2020). More specifically, a growth mindset has been shown to be associated with learning goals and mastery-oriented strategies (Burnette et al., 2013) as well as better academic outcomes (Claro and Loeb, 2019) and well-being (Alvarado et al., 2019). Mindsets have proven to be especially relevant in situations involving challenges and setbacks (Burnette et al., 2013). Namely, people with different beliefs about the malleability of abilities attribute difficulty or failure to different potential causes. While a fixed mindset leads one largely to attribute one's mistakes and setbacks to a lack of fixed ability, a growth mindset leads one mainly to interpret one's mistakes as an indicator of a lack of sufficient effort or the use of an ineffective strategy (Yeager and Dweck, 2012). Individuals can possess different mindsets for different domains, but research has nonetheless demonstrated a certain intraindividual generality for these beliefs across domains (Lewis et al., 2021).

It has been suggested that, during elementary school years, students' mindset meaning systems develop towards greater coherence, as indicated by an increase in associations between mindsets and theoretically relevant constructs, such as goal-orientation (Kinlaw and Kurtz-Costes, 2007). Moreover, research suggests that even though students hold different mindsets about different domains during the first years of elementary school, these mindsets become self-relevant only once the students are older (Gunderson et al., 2017). More specifically, Gunderson et al. (2017) demonstrated that while students generally believed success in math required more fixed ability than did success in reading and writing, younger students believed that this only concerned the success of adults rather than that of their peers. In addition, other studies indicate that people tend to hold a stronger fixed mindset about math than about some other subject domains (e.g., Leslie et al., 2015; Heyder et al., 2020). Additionally, math is one of the subjects that many students consider the most important in school (Dundar and Rapoport, 2014; McGeown and Warhurst, 2020). Math programs become highly cognitively demanding for students after the first years of elementary school (Tsang et al., 2015), and consequently mindsets are especially important during this period. Furthermore, in Finland, where the present study was conducted, notable increases have been shown in students' negative attitudes towards math (disliking math and low math self-efficacy) during elementary and middle school years (Tuohilampi and Hannula, 2013), and concerns about declining math achievement have also been raised (Metsämuuronen and Nousiainen, 2021). Therefore, in the present study, we used an arithmetic task to focus on students' reactions to feedback in the domain of math. As to mindsets, we assessed both general intelligence mindsets and math ability mindsets to examine their subject-domain specificity regarding associations with the attentional neural processing of feedback.

In line with the theory of mindsets as meaning systems that perform an organizing function regarding the interpretation of experiences (Hong et al., 1999), research has demonstrated that mindsets are associated with error-monitoring (Moser et al., 2011; Schroder et al., 2014, 2017) and the attentional neural processing of feedback (Mangels et al., 2006; Puusepp et al., 2021). While automatic allocation of attentional resources to the stimulus cannot be assessed through behavioral or survey measures, event-related potentials (ERPs) provide a covert measure of these processes. ERPs are fluctuations of voltage recorded using an electroencephalogram (EEG) that are time-locked to a certain event (e.g., presentation of a stimulus) or response execution (e.g., the pressing of a button; Woodman, 2010; Kappenman and Luck, 2011).

One of the most frequently examined ERP components elicited by feedback is P300. P300 is a positive-going waveform reflecting the processing of attention-demanding stimulus in general; thus, it is not limited to feedback-stimulus processing (for a review, see Polich, 2007). This waveform peaks at approximately 300–600 ms after the appearance of the eliciting stimulus, and it is assumed to reflect attentional processes and to signal unexpected changes that are relevant for behavioral adjustment. A larger P300 amplitude is associated with greater availability or allocation of attentional resources for processing the stimulus, while a smaller amplitude indicates the reverse (Polich, 2007). As an increase in P300 amplitude reflects greater attention allocation, it has also been associated with the heightened psychological significance of certain stimuli when compared to more neutral stimuli (Gray et al., 2004). In the context of reward and feedback processing, unexpected stimuli or outcomes have been observed to elicit a larger P300 than that produced by anticipated stimuli or outcomes (Hajcak et al., 2005; Wu and Zhou, 2009; for a review, see San Martín, 2012). Furthermore, the size of the outcome (either loss or reward) has been associated with the feedback-related P300 amplitude, with outcomes of a greater magnitude relating to a larger P300 than that elicited by smaller outcomes (San Martín, 2012). Nonetheless, the findings on the effect of feedback or outcome valence on P300 have been somewhat inconsistent, with some studies reporting feedback-related P300 to be greater in the case of positive feedback (adults: Wu and Zhou, 2009; Ernst and Steinhauser, 2012), others finding a larger P300 for negative feedback (children: Arbel, 2020; adults: Butterfield and Mangels, 2003), and some showing it to be insensitive to the valence of the feedback stimulus (children: Ferdinand et al., 2016; Du et al., 2018; adults: Hajcak et al., 2005; Yeung et al., 2005; for a review, see San Martín, 2012). Furthermore, the findings of Buritica et al. (2018) indicate that, in children, differences between the positive- and negative-feedback P300 depend on the task design. Attentional neural processing of feedback has also been shown to associate with learning from corrective feedback, with a greater feedback-related P300 elicited when tasks initially answered incorrectly were later answered correctly than when such tasks were unsuccessfully answered in a retest (Ernst and Steinhauser, 2012).

Another ERP associated with mindset is error-related positivity (Pe). Pe is a positive-going ERP that is elicited on error commission in reaction time tasks peaking, in general, between 200 and 400 ms after an erroneous button press. Pe indicates awareness of committing an error and is assumed to reflect the motivational significance of that error (Overbeek et al., 2005). Pe and P300 are assumed to reflect similar processes—conscious processing of motivationally significant events (Ridderinkhof et al., 2009). Thus, results demonstrating that a greater difference in Pe between erroneous and correct trials is associated with a growth mindset (Moser et al., 2011; Schroder et al., 2017) are in line with the theory of mindsets as meaning systems: for growth-minded individuals, mistakes are motivationally significant for enhancing their ability, as such errors are an indicator of the need for more effort or different strategies (Molden and Dweck, 2006). To our knowledge, there are four studies that have explored the association between mindsets and automatic attention allocation to mistakes. Two of these studies have found a growth mindset to be associated with greater attention allocation to committed errors (compared to correct responses), as indicated by a larger difference between Pe amplitudes for erroneous and correct trials (adults: Moser et al., 2011; school-aged children: Schroder et al., 2017). In their study with experimentally induced growth and fixed mindsets, Schroder et al. (2014) nonetheless produced somewhat different results: a smaller Pe in the growth mindset group compared to the fixed mindset group. Moreover, they found that participants with an induced growth mindset exhibited smaller Pe amplitudes elicited by not only erroneous, but also correct responses. Recently Janssen et al. (2021) suggested that the associations between mindset and Pe found in previous studies might have been confounded with the P300 response elicited by the stop-stimulus in the experimental tasks used. Namely, they found a more fixed mindset to be marginally associated with a larger P300 elicited by the stop-stimulus in a go/no-go task. These results suggest that mindsets might be associated with stimulus processing more generally and not only with error monitoring.

In addition to the aforementioned studies on mindsets and error monitoring, to our knowledge there are two studies that have explored associations between mindsets and the attentional neural processing of feedback (Mangels et al., 2006; Puusepp et al., 2021). Error monitoring and feedback processing could be considered similar processes, with error monitoring requiring internal feedback (it is the person themselves who realizes they have made a mistake, without any external feedback), and feedback processing requiring external feedback. Based on the study by Mangels et al. (2006) on adults, a fixed mindset about intelligence, when compared to a growth mindset, was associated with a larger anterior frontal P300 elicited by negative performance-relevant feedback in a general knowledge test. As this larger P300 was also associated with the endorsement of performance goals, it was assumed to reflect heightened attention to evaluative performance-relevant feedback among fixed-minded participants. In turn, Puusepp et al. (2021) explored the associations between domain-general and domain-specific mindsets and feedback processing among elementary school students. They found a marginally significant unique association between math ability mindsets and the difference between the P300 elicited by negative and positive feedback in an arithmetic task, with general intelligence mindsets demonstrating no such association. Nevertheless, in that study, only the difference between the ERPs elicited by positive and negative feedback was explored, with no inspection of the associations between mindsets and the processing of positive and negative feedback separately.

The current study is part of the project Copernicus—Changing Mindsets about Learning: Connecting Psychological, Educational and Neuroscientific Evidence. This project uses a multidisciplinary approach to investigate the mindsets of elementary school students (Laine et al., 2022) and their parents (Levinthal et al., 2021) as well as the beliefs and pedagogical practices of teachers (Rissanen et al., 2019). Additionally, the project aims to develop an intervention program to be used by teachers in Finland to support the development of their elementary school students' growth mindsets (Rissanen et al., 2021). The main aim of the present study was to explore the development of the associations between elementary school students' mindsets and the attentional neural processing of feedback. More specifically, we aimed to extend the earlier findings of Mangels et al. (2006) and Puusepp et al. (2021) by (a) inspecting the associations between mindset and attention allocation to performance-relevant feedback among children, (b) taking into account the subject-domain-specificity of mindsets regarding these associations, and (c) longitudinally exploring the development of these associations. Therefore, the current study explored the associations between elementary school students' general intelligence mindset and math ability mindset and their P300 responses elicited by performance-relevant positive and negative feedback in an arithmetic task in two consecutive school years. Our main research questions and hypotheses were as follows:

RQ1. How are children's mindsets (general intelligence mindset and math ability mindset) associated with their attention allocation to performance-relevant positive and negative feedback in an arithmetic task? We hypothesized that:

(H1a) mindsets are associated with the attentional neural processing of negative, but not positive, performance-relevant feedback (Mangels et al., 2006; Puusepp et al., 2021),

(H1b) the associations between math ability mindset and feedback-related P300 during an arithmetic task are stronger than the associations between general intelligence mindset and feedback-related P300 during an arithmetic task (Puusepp et al., 2021).

RQ2. How do associations between children's mindsets (general intelligence mindset and math ability mindset) and attention allocation to performance-relevant feedback develop? We hypothesized that:

(H2) the association between mindset and feedback-related P300 strengthens as children age (Kinlaw and Kurtz-Costes, 2007).

2. Materials and methods

2.1. Participants

A total of 104 participants from two Finnish public elementary schools in the Helsinki metropolitan area were initially recruited for this study. One of the schools was situated in a low socioeconomic status (SES) area and the other in a medium SES area (Vilkama et al., 2014). Two outlier participants with P300 amplitudes (measured in grade 3 or 4) exceeding 3 standard deviations from the mean were excluded from the final sample. Participants with complete data from either both years or one year were included in the analyses, resulting in a final sample of 100 participants (50 girls, 45 boys, and 5 who responded "Other"; M_{age} at the beginning of the study = 8.94 years, SD_{age} = 0.42 years, Min_{age} = 8 years, Max_{age} = 11 years). Reasons for missing data included withdrawing from the study, absence from school on the data collection days, or a technical issue during the EEG-recording.

2.2. Measures

2.2.1. Mindsets

For assessing participants' *General Intelligence Mindset (GIM),* four Entity Theory statements from the Implicit Theories of Intelligence Scale (Dweck, 2000) were used (e.g., "You have a certain amount of intelligence, and you cannot really do much to change it"). In order to assess participants' *Math Ability Mindset (MAM)*, the same four Entity Theory statements from the Implicit Theories of Intelligence Scale used for assessing GIM were adapted to be math-specific. Participants indicated the degree to which they agreed with each of the statements by marking one of six circles, which varied in size (ranging from small to big) and were mapped to a 6-point scale (1—do not agree at all . . . 6—completely agree). Four average scores were used; GIM in grade 3 and 4 and MAM in grade 3 and 4. Higher scores indicate a greater endorsement of a growth mindset. The internal reliabilities of the mindset instruments from both years were good (Cronbach's α ranged from 0.76 for GIM in grade 3 to 0.86 for MAM in grade 4).[1]

2.2.2. Arithmetic task

The participants' *P300 responses elicited by feedback* were recorded during the completion of an age-appropriate two-alternative choice arithmetic task (**Figure 1**). Each trial in the task consisted of an arithmetic calculation with one number missing; this calculation was presented at a central location on the computer screen for 3,000 ms. Subsequently, either a correct or incorrect answer was presented in the place of the missing number for a maximum of 3,000 ms. During this 3,000 ms response window, the participants were instructed to use their dominant hand to press one of the two buttons on the response box to indicate whether they thought the number appearing in the calculation was the correct or incorrect answer. If the number on the screen was correct, the participant's response was followed by the correct answer, shown in bold on the monitor for 3,000 ms. If the number presented on the screen was incorrect, this incorrect answer changed into the correct answer, which was also displayed on the screen for 3,000 ms. If the participant responded incorrectly, their response was immediately followed by a feedback tone lasting 100 ms to ensure that the participant was aware of their mistake. If the participant failed to produce a response during the 3,000 ms response window, a time-out message appeared at the center of the screen for 3,000 ms before the calculation of the next trial appeared.

Before the arithmetic task, the participants completed a practice block consisting of five correct trials and five incorrect trials to ensure that they had understood the task. Based on their performance during the practice block, the participants were subsequently administered either an easier (0–5 trials answered correctly) or a more difficult version (6–10 trials answered correctly) of the actual task in order to ensure that the calculations in the task were sufficiently, but not overly, challenging for the participants.

The actual task consisted of two blocks (47 trials in the first block and 46 trials in the second block) with a total of 93 trials. The 93 trials (48 correct calculations and 45 incorrect calculations) were presented in random order to each participant. Between the blocks, the children were permitted a 5- to 10-min refreshment pause. In order to avoid possible motor response confounds in the aggregated data, the positions of the two buttons on the response box were alternated every second experimental day (Grootswagers et al., 2017). The difficulty of the calculations in the arithmetic tasks was adjusted according to the grade level, with the 3rd grade task including only addition and subtraction and 4th grade task also including multiplication and division.

1 As the Implicit Theories of Intelligence Scale was originally recommended for children of 10 years or older (Dweck, 2000, p. 177), we used confirmatory factor analysis to confirm that these two mindsets (GIM and MAM) formed two distinct but correlated factors at both grade levels (see **Supplementary Table 1**). Additionally, we examined whether the associations between mindsets and theoretically related constructs emerged in the present sample (see **Supplementary Table 2**).

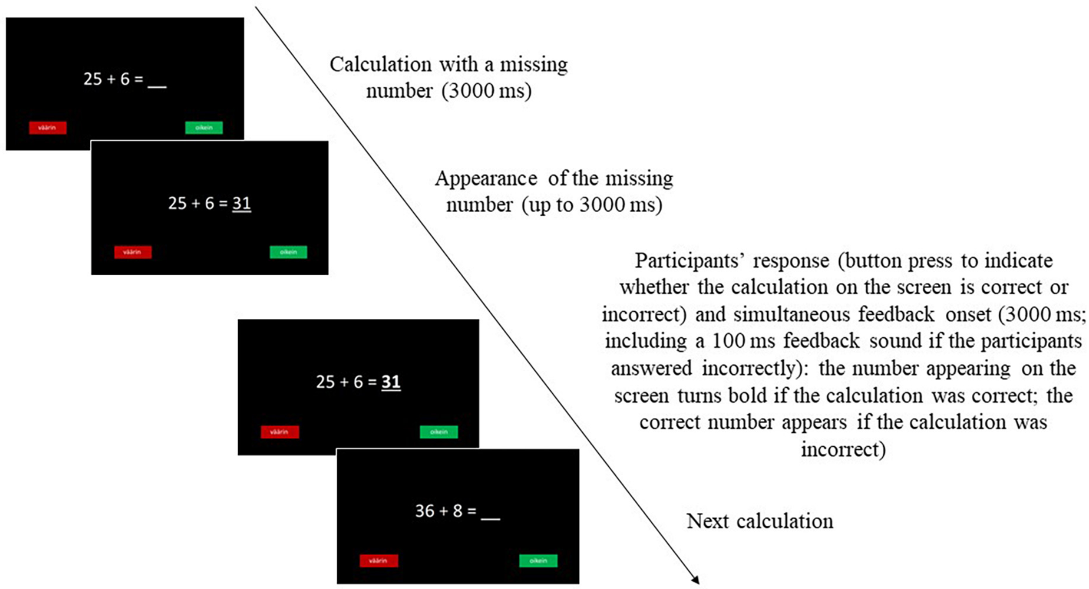

FIGURE 1
Sequence of events in a trial of the two-alternative choice arithmetic task.

2.3. Procedure

The children's participation in the study was voluntary. Written parental consent for the study was obtained. The children and their parents were informed about the research procedures and their right to withdraw their participation at any moment of the study. The University of Helsinki Ethical Review Board reviewed and approved the research project for the study.

The students completed a questionnaire including the mindset scales as part of a longer questionnaire during their regular school activities in the autumn semester of their 3rd and 4th grade. The questionnaires were administered by a researcher who explained the questionnaire procedure with examples of statements with response options. For data collection in grade 3, the researcher read each question and response option aloud as the participants completed the electronic questionnaire on laptops or tablets provided by the school. In grade 4, the participants completed the electronic questionnaire individually during a school lesson. The procedure lasted approximately 40 min.

The psychophysiological recordings were performed by the experimenter(s) in a separate room at the school premises during regular school hours. Before the recordings, the children were briefed about how the experiment would proceed and reminded of their right to withdraw their participation at any moment. After the task and the recording, the children were compensated for their participation with sweets and stickers. The entire procedure lasted for 60-75 min per participant, with the duration of the EEG-recording being approximately 20 min per participant.

2.4. Data recording and processing

Continuous electroencephalographic activity was recorded with portable equipment (BrainVision QuickAmp amplifier) using 32 Ag-AgCl active electrodes (ActiCap, Brain Products, Germany). Electrolyte gel (Signa Gel, Bio-Medical Instruments, Inc., Warren, MI, USA) was used at each electrode. The data were recorded with a BrainVision Recorder at a 250 Hz sampling rate. The Recording reference was Fpz or FCz, depending on the size of the cap used. Afterwards, the EEG data were processed with MATLAB R2019a software (Mathworks, Natick, MA, USA) with the EEGLAB 19.0 toolbox. The signal was band-pass filtered with cutoffs of 0.1 and 30 Hz and segmented into epochs beginning 200 ms before each button press and continuing for 750 ms following each button press. In addition to visual inspection, artifactual epochs were rejected by detecting abnormal trends and abnormal spectra, and eye movement artefacts were removed using independent component analysis (Delorme and Makeig, 2004). Subsequently, the data were re-referenced to the mean of the mastoid electrodes.

Feedback-locked P300 amplitudes were calculated relative to a -150 to -50 ms baseline window, which was also approximately 150–50 ms prior the response (button press), as the time difference between the button press and the feedback stimulus onset was only a few milliseconds. In order to obtain feedback-related ERPs regarding participants' authentic decisions about the accuracy of the math calculations and in order to exclude trials involving accidental button presses, all trials where the reaction time was less than 300 ms after the appearance of the pre-response-stimulus (the answer appearing in place of the missing number of the equation on the screen) were omitted from the analyses (Thomas et al., 1981). In addition, time-out trials were excluded from further analyses. Furthermore, to ensure reliable averages for the ERPs, a minimum of six trials was considered necessary for each participant for both erroneous and correct trials (Pontifex et al., 2010). The average number of correct trials included in the further analyses was 42 (min 20, max 73) per participant in grade 3 and 41 (min 24, max 62) in grade 4. The average number of erroneous trials in grade 3 was 27 (min 6, max 53) per participant, while in grade 4 it was

24 (min 8, max 40) per participant. Subsequently, the averaged ERPs for correct and erroneous trials were visually inspected in order to determine the electrode sites with maximal amplitudes and to calculate the most relevant time windows for the correct- and erroneous trial P300s (Figure 2). Accordingly, feedback-locked grand average P300 amplitudes were calculated for three electrode sites along the scalp midline (Fz, Cz, and Pz). The positive-feedback P300 was calculated as the mean amplitude over a 50 ms time window around each participant's average positive peak between latencies 200 and 400 ms after the onset of the positive feedback stimulus. The negative-feedback P300 was calculated as the mean amplitude over a 50 ms time window around each participant's average positive peak between latencies 300 and 450 ms after negative feedback stimulus onset.

2.5. Overview of data analysis

The descriptive statistics of mindsets, behavioral variables, and P300 were calculated and the distribution of data inspected visually. None of the variables severely violated the normality assumption. Therefore, Pearson correlation was used to inspect the relationships between the study variables. The research questions were answered by using linear mixed modelling (LMM). R package *lme4* was used, and *p*-values were computed with the *lmerTest* package (Kuznetsova et al., 2017), using Satterthwaite's method to estimate degrees of freedom. When statistically significant effects of fixed factors emerged in LMM, the *emmeans* package was used to compute the estimated marginal means, and Bonferroni-corrected post hoc comparisons were performed. When significant effects of continuous variables emerged in LMM, simple slope comparisons were used. To calculate effect sizes (partial epsilon squares), the *effectsize* package was used. The continuous variables were standardized for modeling, and thus standardized coefficients are reported.

Before conducting the main analysis, a model without any fixed predictors was first specified to estimate how much variance in P300 amplitude could be attributed to individual differences between participants within classrooms and between different classes (i.e., random effects of participant and class). As this model demonstrated a low variance of P300 to be explained by the nestedness of participants in classrooms, subsequent analyses were conducted without random effects of class. Second, the effects of background variables (grade level, feedback type, electrode site) and the behavioral measure of task accuracy on P300 were inspected using LMM (for the results of this LMM, see **Supplementary Table 3**). Based on these results, the main models were constructed, with grade level (3rd or 4th grade), feedback condition (positive or negative feedback) and electrode site (Fz, Cz, or Pz) used as within-subject fixed factors. Overall accuracy on the task and GIM or MAM scores were included as between-subject fixed continuous predictors. As to random effects in the main models on longitudinal data, (1) a random intercept by the participant and (2) feedback type, grade level and GIM or MAM as random slopes by the participant were included. In this way, random effects resulting from repeated measures regarding the same participants were accounted for in the models, allowing for between-subject variability. These models were inspected for potentially influential extreme values, normality of residuals, homoscedasticity and multicollinearity, with no violations of the assumptions being found.

TABLE 1 Descriptive statistics for study variables from both years.

Variable	*n*	*M (SD)*	*Min*	*Max*
1. Positive-fb P300 at Fz (μV) in grade 3	100	13.04 (12.66)	−19.58	51.96
2. Positive-fb P300 at Cz (μV) in grade 3	100	13.33 (13.04)	−15.62	48.15
3. Positive-fb P300 at Pz (μV) in grade 3	100	10.19 (13.38)	−16.30	40.64
4. Negative-fb P300 at Fz (μV) in grade 3	100	11.22 (14.61)	−37.83	56.89
5. Negative-fb P300 at Cz (μV) in grade 3	100	14.86 (14.29)	−23.85	49.83
6. Negative-fb P300 at Pz (μV) in grade 3	100	11.42 (12.13)	−24.85	47.96
7. Task accuracy (%) in grade 3	100	60.5 (10.5)	38.1	88.8
8. General intelligence mindset in grade 3	99	3.65 (1.20)	1.00	6.00
9. Math ability mindset in grade 3	99	4.15 (1.20)	1.25	6.00
10. Positive-fb P300 at Fz (μV) in grade 4	96	12.95 (8.36)	−6.85	34.44
11. Positive-fb P300 at Cz (μV) in grade 4	96	14.35 (10.26)	−10.32	38.32
12. Positive-fb P300 at Pz (μV) in grade 4	96	10.82 (10.19)	−9.45	35.22
13. Negative-fb P300 at Fz (μV) in grade 4	96	15.79 (11.39)	−10.25	57.85
14. Negative-fb P300 at Cz (μV) in grade 4	96	19.30 (13.22)	−6.26	55.78
15. Negative-fb P300 at Pz (μV) in grade 4	96	14.52 (10.91)	−11.16	43.54
16. Task accuracy (%) in grade 4	97	64.8 (9.5)	46.7	92.3
17. General intelligence mindset in grade 4	97	3.91 (1.26)	1.25	6.00
18. Math ability mindset in grade 4	97	4.36 (1.20)	1.00	6.00

fb, feedback.

3. Results

3.1. Mindsets

A range of mindset endorsements was observed, with participants' GIM and MAM scores falling between fixed and growth extremes (Table 1). Positive correlations between GIM and MAM were observed both in grade 3 ($r = 0.43$, $p < 0.001$) and grade 4 ($r = 0.67$, $p < 0.001$; Table 2). Both GIM and MAM showed stability over the two years, as indicated by the within-construct correlations over the two measurement points ($r = 0.22$, $p = 0.035$; $r = 0.35$, $p < 0.001$, respectively).

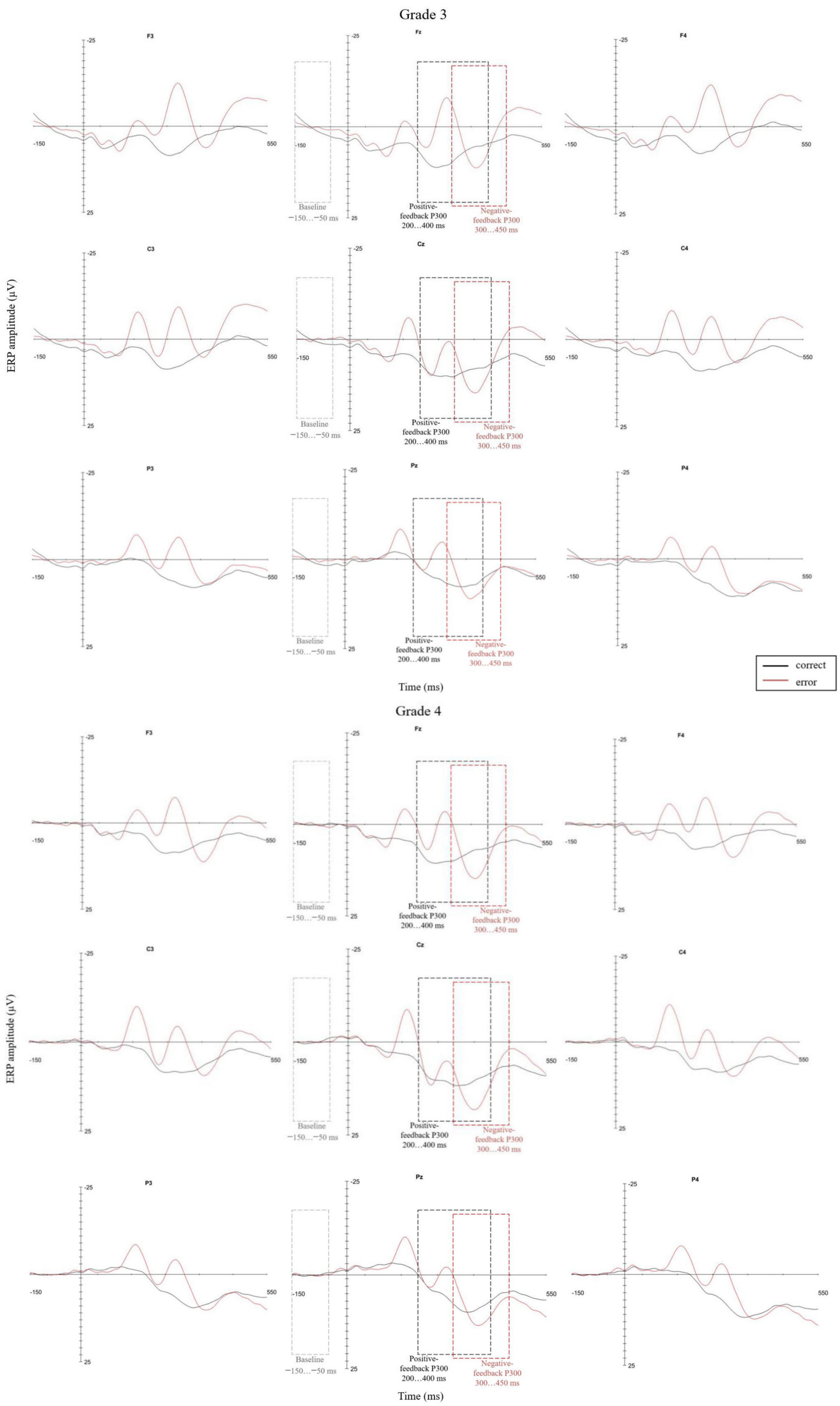

FIGURE 2
Feedback-locked waveforms for positive and negative feedback trials at both grade levels with indicated baseline and P300 time windows at frontal, central, and parietal electrodes. The 0 point on the time scale represents the feedback stimulus onset. The P300 amplitudes were collected based on individual peak latencies: positive-feedback P300 within the 200–400 ms and negative-feedback P300 within the 300–450 ms time window after feedback stimulus onset.

3.2. Behavioral data

In the 3rd grade, the participants were correct, on average, in 60.5% (SD = 10.5%) of the trials (excluding timed-out trials), with the average accuracy in the group of students completing the easier version of the task (n = 38) being 57.4% (SD = 8.2%) and the accuracy for the more difficult version (n = 62) being 62.4% (SD = 11.4%). In the 4th grade, the average task accuracy was 64.8%

TABLE 2 Correlations between study variables from grades 3 and 4.

Variable	1	2	3	4	5	6	7	8	9
1. Positive-fb P300 at Fz (μV)	**0.25***	0.80***	0.62***	0.43***	0.45***	0.44***	0.00	−0.29**	−0.17
2. Positive-fb P300 at Cz (μV)	0.89***	**0.38*** **	0.85***	0.32**	0.48***	0.48***	−0.14	−0.31**	−0.25*
3. Positive-fb P300 at Pz (μV)	0.72***	0.86***	**0.46*** **	0.12	0.30**	0.47**	−0.28**	−0.27**	−0.27*
4. Negative-fb P300 at Fz (μV)	0.61***	0.48***	0.30**	**0.32** **	0.78***	0.61***	0.34***	−0.10	0.13
5. Negative-fb P300 at Cz (μV)	0.58***	0.57***	0.40***	0.81***	**0.38*** **	0.83***	0.31**	−0.09	0.01
6. Negative-fb P300 at Pz (μV)	0.52***	0.57***	0.61***	0.63***	0.80***	**0.20***	0.22*	−0.10	−0.05
7. Task accuracy (%)	−0.07	−0.17†	−0.24*	0.03	0.05	−0.08	**0.58*** **	0.11	0.25*
8. General intelligence mindset	−0.05	−0.10	−0.17†	0.04	−0.02	−0.03	−0.02	**0.22***	0.67***
9. Math ability mindset	0.05	−0.09	−0.22*	0.16	0.03	−0.09	0.10	0.43***	**0.35*** **

fb, feedback. Correlations between variables in grade 3 are presented under the diagonal, while correlations between variables in grade 4 are shown above the diagonal. Within-construct correlations are presented in bold in the diagonal. †$p < 0.10$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

(SD = 9.5%), with the average accuracy in the group of students completing the easier version of the task (n = 34) being 64.0% (SD = 8.4%) and the accuracy for the more difficult version (n = 63) being 65.3% (SD = 10.0%). Regarding associations with mindset, a higher MAM was associated with greater task accuracy in grade 4 (r = 0.25, p = 0.015), while this association was not significant in grade 3 (Table 2).

3.3. Feedback-related P300

Regarding the random effects of the models, the variance explained by the nestedness of measurements in participants for the intercept of P300 was 0.60-0.65, and regarding the slopes it was 0.04-0.72 (see Supplementary Table 4 for details on the random effects).

3.3.1. Associations between P300 and mindsets

In general, the effects of GIM and MAM on P300 were both similar, although in contrast to MAM, GIM also exerted a marginal main effect on P300 (Table 3), with a higher growth mindset about general intelligence marginally associating with a smaller P300 (β = -0.10, SE = 0.08). Significant interaction effects of mindsets and feedback type as well as marginally significant interaction effects of mindsets and grade level emerged (Table 3). Simple slope comparisons revealed that the effect of mindsets (both GIM and MAM) on P300 differed between feedback types at both grade levels ($t \leq$ -2.00, $p \leq$ 0.045, for all). More specifically, a stronger growth mindset was associated with a smaller P300 in the case of positive feedback, while based on 95% confidence intervals a similar trend for the effect of GIM on negative-feedback P300 in grade 4 was observed (Table 4; see also Figures 3, 4). Additionally, the interaction effects of mindsets and grade level only approached significance, and the confidence intervals indicate that it was only in grade 4 that the effects of mindsets on P300 differed from 0 (Table 4).

3.3.2. Effects of feedback type, electrode site, grade level and task accuracy on P300

Overall, both P300 models (the model including GIM as a predictor and the model with MAM as a predictor) resulted in significant main effects of feedback and electrode site and significant interaction effects between feedback type and grade level as well as between feedback type and electrode site (Table 3). *Post-hoc* tests revealed that while there was no significant difference between positive- and negative-feedback P300 in grade 3 ($t \geq$ -0.24, $p \geq$ 0.811, for both models), in grade 4, P300 was larger in case of negative feedback when compared to positive feedback ($t \leq$ -5.30, $p <$ 0.001, for both models; see also Table 1). As to the effect of electrode site, negative-feedback P300 (averaged across grade levels) was larger at Cz than at Fz ($t \geq$ 5.43, $p <$ 0.001, for both models) and at Pz ($t \geq$ 6.24, $p <$ 0.001, for both models). Positive-feedback P300 was larger at Fz and Cz when compared to Pz ($t \geq$ 3.57, $p \leq$ 0.003, for all; see also Table 1).

Regarding the effects of participants' accuracy on the task, both models again resulted in overall similar results. More specifically, both models revealed significant interactions between task accuracy and feedback as well as task accuracy and electrode site (Table 3). The interaction effect of task accuracy and grade level reached significance only in the model including MAM as a predictor, although it was marginal in the model including GIM as predictor (Table 3). Additionally, there was a significant three-way interaction effect of accuracy, feedback type and grade level in both models (Table 3). According to simple slope comparisons, the effect of accuracy on P300 differed between positive and negative feedback at both grade levels ($t \leq$ -3.06, $p \leq$ 0.007, for all). More specifically, higher accuracy was associated with a smaller positive-feedback P300 (see Supplementary Table 5 for the coefficients of the effects of accuracy on both feedback types at both grade levels). In the case of negative feedback, the effect of accuracy on P300 differed significantly between grade levels ($t \leq$ -2.97, $p \leq$ 0.011, for both models), with higher accuracy associated with a greater negative-feedback P300 only in grade 4 (Supplementary Table 5). As to electrode sites, the effect of accuracy on P300 (averaged across grade levels) did not differ between Fz and Cz ($t \geq$ -1.42, $p \geq$ 0.315, for all), but, in the case of positive feedback, the effect of accuracy emerged at Pz ($t \geq$ 3.32, $p \leq$ 0.006, for all; see Supplementary Table 6 for the coefficients of the effects of accuracy at each electrode site), while, in the case of negative feedback, it only emerged

TABLE 3 Results of linear mixed models predicting P300 amplitude.

Fixed factor	General intelligence mindset					Math ability mindset				
	df_{Num}	df_{Den}	F	p	ϵ^2_p	df_{Num}	df_{Den}	F	p	ϵ^2_p
Mindset	1	53.81	3.46	0.068	0.04	1	111.63	2.05	0.155	0.00
Feedback type	1	91.80	9.62	**0.003**	0.08	1	92.61	9.77	**0.002**	0.09
Grade level	1	92.28	0.00	0.989	0.00	1	85.89	0.01	0.926	0.00
Electrode site	2	843.55	31.86	**<0.001**	0.07	2	844.30	31.61	**<0.001**	0.07
Feedback type × electrode site	2	843.55	4.38	**0.013**	0.00	2	844.30	4.35	**0.013**	0.00
Task accuracy	1	167.20	0.04	0.833	0.00	1	166.55	0.22	0.637	0.00
Mindset × feedback type	1	715.60	10.57	**0.001**	0.01	1	558.80	7.79	**0.005**	0.01
Mindset × grade level	1	134.08	2.93	0.089	0.01	1	130.46	3.36	0.069	0.02
Feedback type × grade level	1	865.51	34.67	**<0.001**	0.04	1	867.19	33.71	**<0.001**	0.04
Feedback type × task accuracy	1	348.36	46.27	**<0.001**	0.11	1	339.34	42.17	**<0.001**	0.11
Mindset × feedback type × grade level	1	923.86	0.39	0.533	0.00	1	907.86	0.00	0.972	0.00
Task accuracy × grade level	1	118.07	2.93	0.089	0.02	1	105.84	4.72	**0.032**	0.03
Task accuracy × electrode site	2	843.55	11.88	**<0.001**	0.03	2	844.30	11.78	**<0.001**	0.02
Task accuracy × feedback type × grade level	1	938.98	16.35	**<0.001**	0.02	1	943.32	15.58	**<0.001**	0.02

df_{Num} indicates the degrees of freedom numerator. df_{Den} indicates the degrees of freedom denominator. Significant p-values are marked in bold.

TABLE 4 Effects of mindsets on positive- and negative-feedback P300 in grade 3 and 4 based on follow-up simple slope comparisons.

Predictor	Positive-feedback P300					Negative-feedback P300				
	β	SE	95% CI		p	β	SE	95% CI		p
			LL	UL				LL	UL	
GIM in grade 3	−0.10	0.08	−0.27	0.06	0.235	0.06	0.09	−0.11	0.23	0.489
GIM in grade 4	−0.26	0.08	−0.42	−0.09	**0.002**	−0.14	0.08	−0.30	0.02	0.086
MAM in grade 3	−0.05	0.08	−0.21	0.10	0.527	0.07	0.08	−0.08	0.23	0.376
MAM in grade 4	−0.24	0.09	−0.41	−0.07	**0.006**	−0.11	0.09	−0.28	0.06	0.205

Significant p-values are marked in bold. GIM, general intelligence mindset. MAM, math ability mindset.

at Cz and Fz ($t \geq 3.32$, $p \leq 0.006$, for all; Supplementary Table 6).

4. Discussion

The main aim of the present study was to explore the development of the associations between elementary school students' mindsets and the attentional neural processing of feedback. More specifically, we focused on the development of associations between elementary school students' general intelligence mindset and math ability mindset and attention allocation to feedback as indicated by their P300 response elicited by both positive and negative performance-relevant feedback in an arithmetic task. We found that a more fixed mindset about both general intelligence and math ability was associated with greater attention allocation to positive feedback, with these associations being driven by the effects of mindsets on attention allocation to positive feedback in grade 4. Regarding the participants' general intelligence mindset, a similar trend was also observed in the case of negative feedback once the children were older. Our results also indicate that the effects of both mindsets on attention allocated to feedback were marginally stronger for the participants when they were in grade 4.

4.1. Mindsets

At both grade levels, we found that students with a stronger growth mindset about general intelligence also displayed more of a growth mindset about math ability. This is in line with research indicating a certain intraindividual generality of mindsets regarding different domains (Lewis et al., 2021). Additionally, both mindsets showed weak to moderate stability over the two assessment points, which is in line with earlier findings on elementary school students (Pomerantz and Saxon, 2001; Kim and Park, 2021). In grade 4, a stronger growth mindset about math ability was associated with higher overall accuracy on the arithmetic task, while this association did not emerge in grade 3. This result possibly reflects the development of students' mindsets into more coherent meaning systems during elementary school years (Kinlaw and Kurtz-Costes, 2007). The association between overall accuracy on the arithmetic task and a math ability mindset, but not a general intelligence mindset, is in line with the meta-analysis

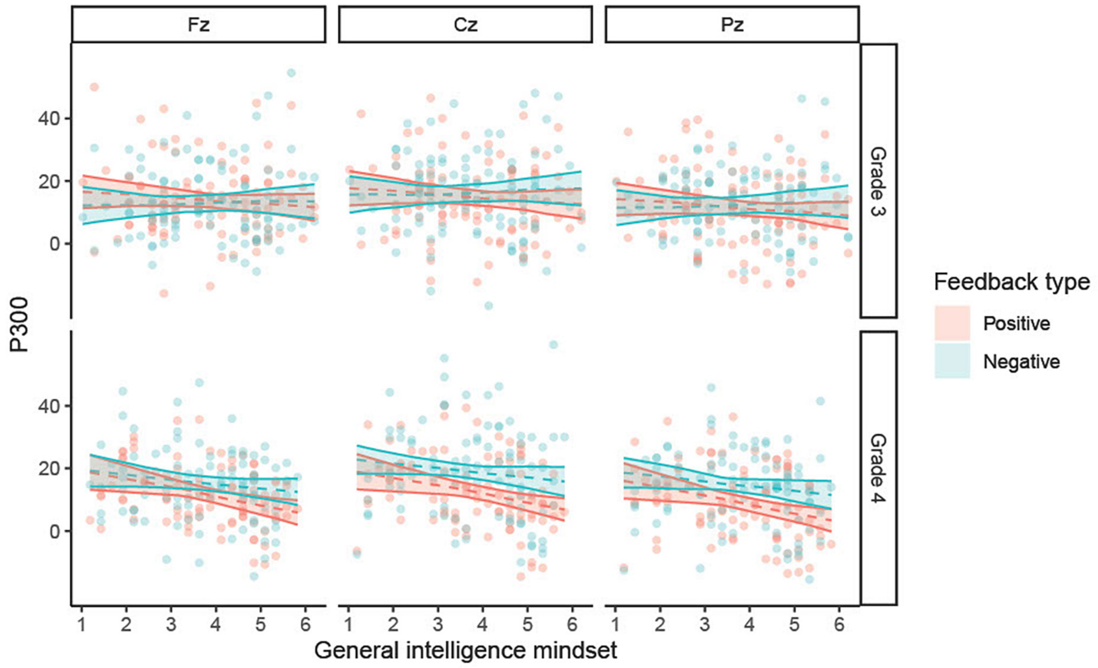

FIGURE 3
General intelligence mindset and P300 responses to positive and negative feedback in grades 3 and 4 at electrodes Fz, Cz, and Pz. Observations are shown as points, and LMM model predictions based on fixed effects are shown as dashed lines with bootstrapped 95% confidence bands.

performed by Costa and Faria (2018), who concluded that students' subject-domain-specific mindsets were more strongly associated with their achievement in the respective subject-domain than were mindsets related to another domain.

4.2. Associations between mindsets and P300 elicited by positive and negative feedback

Partially contradicting our expectations regarding the effect of mindsets on P300 in the case of different feedback types (H1a), we found that students with a more fixed mindset about general intelligence as well as math ability allocated greater attention to positive feedback, as indicated by a larger P300 elicited by positive feedback. These associations were driven by the effects of mindsets on positive-feedback P300 in grade 4. Regarding the participants' general intelligence mindset, a similar trend was observed in the case of negative feedback when the children were older. The direction of these associations between mindsets and feedback-related P300 found in the present study are in line with the single earlier study on mindsets and feedback processing analyzing positive- and negative-feedback P300 separately (Mangels et al., 2006). Mangels et al. (2006) studied these associations among adults using a general knowledge task and found that a stronger fixed mindset was associated with more attention allocated to negative feedback, as indicated by a larger P300 elicited by negative feedback stimulus. Nevertheless, while the association between mindset and attention allocation to negative feedback was expected (although found to be marginal in our study), our results on the associations with attention allocated to positive feedback diverge from those of Mangels et al. (2006), as no such association emerged in their study. One possible explanation for these differences relates to the relevance of the experimental tasks to the daily lives of the participants. Mangels et al. (2006) conducted their study among undergraduates and used general knowledge questions from a variety of domains, while, in the present study on 3rd and 4th graders, we focused on the subject-domain of math. Math is a highly relevant subject-domain for elementary school students—they attend math classes regularly and consider math to be important (Tuohilampi and Hannula, 2013; McGeown and Warhurst, 2020). Therefore, in Mangels et al. (2006), it is possible that the effects of mindset on positive-feedback P300 failed to emerge because of the low relevance of the task to the daily lives of the participants. Compared to neutral stimuli, self-relevant stimuli have been shown to receive more attentional resources, as indicated by a larger P300 (Gray et al., 2004). Therefore, the greater attention allocated to feedback in the case of students holding a more fixed mindset could possibly reflect the higher self-relevance of this feedback information to them. Another possibility is that a fixed mindset may result in feedback being experienced as threatening in general. In adults, threat stimuli have been shown to elicit a larger P300 than non-threat stimuli (Wang et al., 2021), and a stronger fixed mindset among undergraduates has been shown to relate to a higher perceived threat of negative feedback (Zingoni and Byron, 2017). P300 is consistently shown to be greater for outcomes of a large magnitude than for outcomes of a small magnitude, independent of the valence of the outcome (for a review, see San Martín, 2012). Therefore, the results of the present study could be due to fixed-minded students experiencing feedback to be an outcome of greater magnitude than do growth-minded students, which is possibly a reflection of the greater self-relevance or perceived threat of the feedback stimuli for these students.

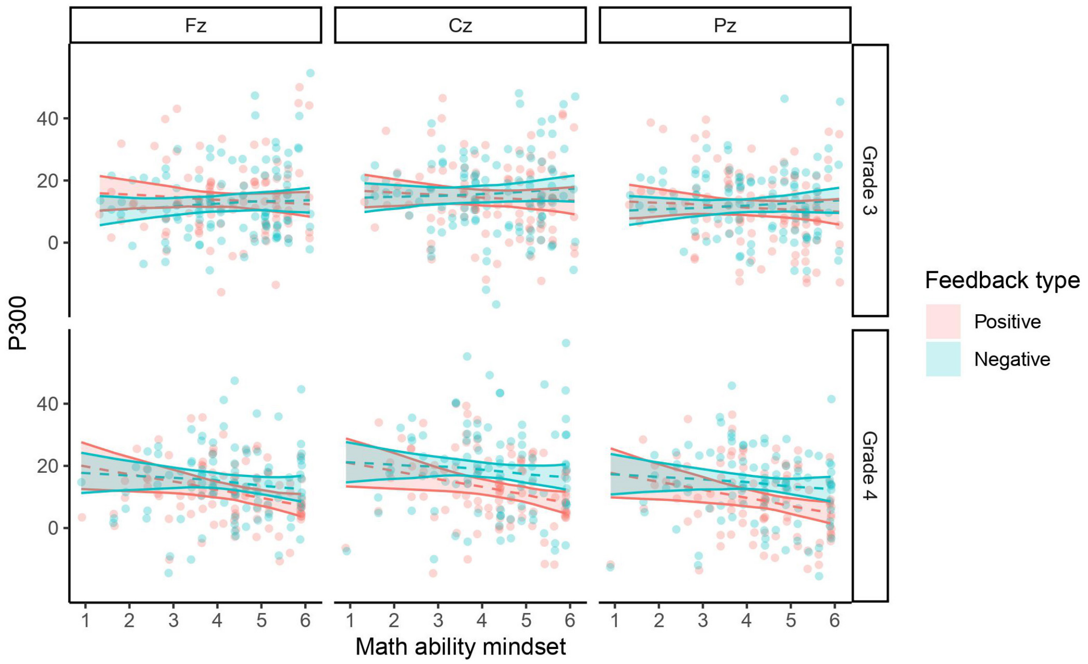

FIGURE 4
Math ability mindset and P300 responses to positive and negative feedback in grades 3 and 4 at electrodes Fz, Cz, and Pz. Observations are shown as points, and LMM model predictions based on fixed effects are shown as dashed lines with bootstrapped 95% confidence bands.

Another possible explanation concerns more general stimulus processing in stressful situations. Namely, a recent study conducted by Janssen et al. (2021) among adults found a fixed mindset to be marginally associated with a larger P300 elicited by the stop-stimulus in a go/no-go task. In an earlier study, Schroder et al. (2014) also demonstrated an association between experimentally induced mindsets and the processing of task-relevant stimuli, although they found that a fixed mindset was associated with a smaller P300 than a growth mindset. As suggested by Janssen et al. (2021), these inconsistencies regarding associations could reflect the effects of contextual factors. For example, whether individuals holding a fixed mindset learn from negative feedback seems to depend on whether the feedback they receive is contextualized as informative or evaluative (Bejjani et al., 2019). In the present study, participants' ERPs were recorded as they completed an arithmetic task where they made errors and received performance-relevant feedback throughout the task. It is probable that the majority of students considered the feedback to be evaluative and therefore experienced the task situation as somewhat stress-inducing. In the study by Janssen et al. (2021), the participants had completed a stress-inducing arithmetic task immediately prior to data collection from the go/no-go task. Both of these studies demonstrated a similar direction for the association between mindset and attention allocation. Therefore, it is possible that these findings reflect the effect of mindsets on stimulus processing more generally when it comes to stressful situations. Nevertheless, as there was only a marginal effect on negative-feedback P300, and this only emerged in case of a general intelligence mindset, these results should be considered with caution and require replication.

The reason for our failure to find clear effects of mindsets on negative-feedback P300 is possibly due to the confounding effects of expectations regarding the negative feedback stimulus. Namely, in the case of higher accuracy in the task, the negative-feedback stimulus was presented less often and thus was probably less expected by the participant. Participants' accuracy was associated with their P300 responses, with this association being more pronounced in grade 4 in the case of negative feedback (for a longer discussion on the effects of task accuracy, see below). It was also in grade 4 that participants' math ability mindset was positively associated with their accuracy in the arithmetic task. Nevertheless, no stronger effect of a math ability mindset on attention allocation, when compared to a general intelligence mindset, emerged in the present study (H1b). The study by Puusepp et al. (2021) used the same experimental design and 3rd grade cross-sectional data from the same sample analyzed in the present study. However, they demonstrated a marginal unique effect of a math ability mindset on the difference between P300 elicited by positive and negative feedback when controlling for the effect of general intelligence mindset. Nevertheless, the researchers focused on examining the relative effects of a general intelligence and math ability mindset and did not control for the potentially confounding effects of task accuracy. The results of the present study indicate that when it comes to attention allocated to feedback in math, it is the individual's general growth or fixed mindset tendency, rather than the domain-specific aspects of their math ability mindset, that is associated with their brain responses (Lewis et al., 2021).

4.3. Development of the associations between mindsets and feedback-related P300

Regarding both general intelligence mindset and math ability mindset, we observed a marginal increase in the association between mindsets and attention allocation to feedback as the students aged (H2). Researchers have suggested that, during the first years of elementary school, students' mindset meaning systems are still developing towards a greater coherence (Kinlaw and Kurtz-Costes, 2007). More specifically, with their cross-sectional data, Kinlaw and Kurtz-Costes (2007) demonstrated that 2nd graders' goal-orientation is more in line with their mindsets when compared to preschoolers. Our longitudinal results demonstrating a marginal increase in the association between students' mindsets and their attention allocation to feedback could reflect a similar developmental trend. It is possible that the one year between measurement points used in the present study was too short a period to observe a significant developmental effect. Nevertheless, as the effect demonstrated in our study was only marginal, our results should be considered with caution and require replication.

4.4. P300 responses: Effects of grade level, feedback, electrode site and task accuracy

When analyzing the development of the amplitude of P300 responses, we found no overall differences between 3rd and 4th grade students. Nonetheless, a large-scale study by Dinteren et al. (2014) indicates that the amplitudes of P300 responses (elicited by auditory stimulus) continue to increase until the age of 21. It is possible that one year is a too short period to catch such a developmental trend. Additionally, Dinteren et al. (2014) used a different paradigm than that employed by the present study.

When investigating the neural processing of positive and negative feedback, we found that the P300 responses elicited by such feedback did not differ among students in grade 3, but, in grade 4, greater P300 amplitudes were elicited by negative feedback than by positive feedback. Earlier findings on the effects of outcome valence on P300 have been mixed (children: e.g., Buritica et al., 2018; Arbel, 2020; adults: e.g., Butterfield and Mangels, 2003; Hajcak et al., 2005; Ernst and Steinhauser, 2012; for a review, see San Martín, 2012). At least among adults, a greater P300 amplitude has been shown to associate with the heightened psychological significance of the stimulus (Gray et al., 2004). Therefore, it is possible that, as students age, the difference between the subjective significance of positive and negative feedback in math becomes greater for them. Moreover, the greater P300 elicited by negative rather than positive feedback in grade 4 possibly reflects the increased salience of negative performance feedback in math compared to positive feedback.

Regarding electrode sites, we found negative-feedback P300 to be greatest at the central site and positive-feedback P300 to be larger at the frontal and central sites than at the parietal site. In line with this result, Wu and Zhou (2009) and Mangels et al. (2006) found P300 to be maximal at the central site, although Ferdinand et al. (2016) produced conflicting results. As to participants' overall accuracy in the task, we found higher accuracy to be associated with a smaller positive-feedback P300 at the parietal site. As to negative feedback, it was only in grade 4 that higher accuracy was associated with a larger negative-feedback P300, with this effect emerging only at the frontal and central site. Earlier studies among adults (Hajcak et al., 2005; Wu and Zhou, 2009; for a review, see San Martín, 2012) as well as children (Ladish and Polich, 1989; but see also Ferdinand et al., 2016) have found P300 amplitude to be sensitive to the probability of the stimulus, with expected stimuli eliciting smaller P300 responses compared to unexpected stimuli. In the case of higher accuracy in the task, the negative-feedback stimulus is presented less frequently and thus is possibly less expected by the participant. Therefore, the positive association between task accuracy and negative-feedback P300 as well as the negative association between task accuracy and positive-feedback P300 probably reflect the effect of expectations about the negative and positive feedback stimulus on P300.

4.5. Limitations and practical implications

There are several limitations that should be borne in mind when interpreting the results of the present study. First, in contrast to positive feedback, negative feedback included a feedback sound. Although this difference between the two feedback types somewhat limits the comparison of attention allocation to positive and negative feedback, we prioritized the clarity of the feedback type for the participants. Therefore, we used the feedback sound in the case of negative feedback to ensure that the participants were clearly aware that they had made an error. Therefore, it is possible that the confounding effect of the negative feedback sound explains why we only observed a marginal effect of mindset on negative-feedback P300, while the effects on positive-feedback P300 were more pronounced.

Second, just as overall task accuracy varied between participants, so did the frequency of the receipt of negative and positive feedback. As stated earlier, the probability of the stimulus affects the elicited P300 response (Hajcak et al., 2005; Wu and Zhou, 2009), and therefore the findings of the present study might be confounded by the effect of stimulus probability on attention allocation, although we did account for task accuracy in our models. While predetermined equal frequencies for negative and positive feedback could have been used, we prioritized participants' experience of the truthfulness of the feedback and therefore presented them with the actual feedback regarding their responses. In future, algorithms could be used to continuously adjust the difficulty of the arithmetic task to the participant's performance, ensuring relatively equal levels of task accuracy among the participants. This would enable the avoidance of the potentially confounding effects of the frequency of both feedback stimuli and therefore allow the effects of mindsets to be assessed more accurately.

Third, in the case of negative feedback in the present study, performance-relevant (information on the accuracy of the response) and corrective feedback (information on the correct response) were presented simultaneously. In future, these two feedback types should be presented sequentially, enabling the inspection of the effects of mindsets on attention allocation to both performance-relevant as well as corrective feedback.

Fourth, we did not assess participants' subjective experiences during the experiment. Future studies could ask participants to report, for example, their level of enjoyment or anxiety during the task, as inspecting associations between these self-reports, mindsets, and P300 would enable more informative inferences to be made regarding the associations between mindsets and attention allocation.

Finally, students' mindsets were assessed using self-report measures. However, research has shown that the use of self-report questionnaires among young children might be problematic, as such children may experience difficulties understanding the questions and engaging in the self-reflection necessary to answer the questions (Borgers et al., 2000). Nevertheless, in the present study, we used different sized circles that mapped to a 6-point scale to help the participants more easily report their agreement with the statements. We also used example statements to ensure the participants understood how to indicate their agreement with the questionnaire items. Additionally, in the 3rd grade, the questions were read out by the researcher one by one. Moreover, at both grade levels, the two-factor models of correlated factors fit the mindset data well (see **Supplementary Table 1**), and the internal consistencies of the scales ranged from acceptable to very good. In addition, we demonstrated that both mindsets were correlated with multiple theoretically relevant measures at both grade levels (see **Supplementary Table 2**).

As to the practical implications of our results, the present study is rather limited, as it only explored the associations between mindsets and performance-relevant feedback. The present findings and earlier research demonstrating the role of mindsets regarding perceptions of feedback (Zingoni and Byron, 2017) suggest that similar feedback can be perceived differently by individual learners, possibly leading to more adaptive behaviors among some students and less adaptive reactions among others. In addition, earlier research has demonstrated the importance of the type of feedback children receive regarding their learning behavior and the development of their mindsets. More specifically, receiving feedback focused on one's fixed qualities (person-oriented feedback) seems to lead to lower task persistence, endorsement of performance goals, and a fixed mindset (e.g., Mueller and Dweck, 1998; for a review, see Haimovitz and Dweck, 2017). Feedback regarding one's effort and strategies (process-oriented feedback), on the other hand, is suggested to lead to higher task persistence and endorsement of learning goals and growth mindset (e.g., Mueller and Dweck, 1998; Gunderson et al., 2013; for a review, see Haimovitz and Dweck, 2017). In the current study, the feedback was neither person- nor process-oriented; rather, it provided information solely about the participants' performance on each trial. It is possible that students holding a more fixed mindset tend to experience such neutral—neither process- nor person-oriented—feedback as more self-relevant than do growth-minded students. Hence, in contrast to growth-minded students, fixed-minded students may experience exclusively performance-relevant feedback as rather similar to person-oriented feedback—as indicative of their fixed ability. This highlights the need for awareness of the potential impacts of feedback on students, as well as the context of feedback, which might be perceived as more threatening by students holding a fixed mindset. It is plausible that providing process-oriented feedback, instead of feedback containing information solely on the current performance, would guide fixed-minded students to view their current performance as part of a long-term learning process and thus support these students in developing a more growth-oriented mindset (Haimovitz and Dweck, 2017; see Wisniewski et al., 2020 for a meta-analysis on the effects of feedback type on student outcomes). Nevertheless, as the current study is limited to performance-relevant feedback, it remains for future research to explore whether the associations between mindsets and attention allocation to process-oriented feedback differ from the associations found in the present study. Additionally, our results emphasize the need to examine the associations between mindsets and the attentional processing of stimuli more generally; moreover, they highlight the importance of exploring the potential effects of contextual factors.

In sum, the findings of the present study demonstrated the association between elementary school students' fixed mindsets about general intelligence and math ability and greater attention allocated to positive feedback in an arithmetic task, with a similar trend identified for the effect of a general intelligence mindset in the case of negative feedback among older children. These results, although tentative and with small effect sizes, suggest that the perspective should be widened to explore the effects of students' mindsets on their experiences more generally rather than focusing primarily on situations involving setbacks.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the University of Helsinki Ethical Review Board. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

IP, MH, TK, EK, SL, and KT planned the research design. IP collected the data and wrote the manuscript. IP, TL, and TT pre-processed the data and conducted the analyses. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Influence of game-based learning in mathematics education on the students' cognitive and affective domain: A systematic review

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Introduction: Game-based learning (GBL) is one of the modern trends in education in the 21st century. Numerous research studies have been carried out to investigate the influence of teaching on the students' academic attainment. It is crucial to integrate the cognitive and affective domains into teaching and learning strategies. This study aims to review journal articles from 2018 to 2022 concerning the influence of GBL in mathematics T&L on the students' cognitive and affective domains.

Methods: A research methodology based on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was used for the survey on the basis of the Scopus and Web of Science (WOS) databases wherein 773 articles relating to game-based learning (GBL) in mathematics were discovered. Based on the study topic, study design, study technique, and analysis, only 28 open-access articles were chosen for further evaluation. Two types of cognitive domain and five types of affective domain were identified as related to the implications of GBL on the students' T&L of mathematics.

Results: The study results show that GBL has positively impacted students when they are learning mathematics. It is comprised of two types of cognitive domain (knowledge and mathematical skills) and five types of affective domain (achievement, attitude, motivation, interest, and engagement). The findings of this study are anticipated to encourage educators in the classrooms more effectively.

Discussion: GBL in education is now one of the major learning trends of the 21st century. Since 2019, the number of studies relating to game-based learning has increased. There is an influence on the cognitive and affective domains due to T&L Mathematics utilizing a game-based learning (GBL) approach.

KEYWORDS

affective domain, cognitive domain, game-based learning, mathematics education, teaching and learning

1. Introduction

Educational transformation is necessary because the success of said economic transformation is very much dependent on the successfulness of a futuristic education plan (Leal Filho et al., 2018). Globalization has formed a new path in worldwide education, and teachers play an active role in the teaching and learning process. In this regard, pedagogy is stressing more about the roles of the students in the learning sessions, specifically how it is compatible with the 21st century learning methods (Amran et al., 2019). According to Kamarudin et al. (2019), the level of student interest in teaching and learning is low when the conventional approach is employed. Consequently, teaching methods and techniques are essential for becoming a teacher who can impart knowledge to their pupils using a variety of engaging approaches and strategies. Teachers must employ the most effective method for imparting knowledge.

Subsequently, learning is intimately tied to the learning domains (Bloom et al., 1956) and has been introduced to education to encourage higher order thinking (Bitok, 2020). It encompasses the cognitive, affective, and psychomotor domains specifically. The cognitive domain is concerned with the intellectual growth of students, the affective domain involves the development of the students' attitudes, feelings, and values, while the psychomotor domain involves the physical development of the students. In this scenario, the cognitive and emotive domains of the pupils also influence the effectiveness of the GBL method.

GBL in education is now one of the major learning trends of the 21st century (Ahmad and Iksan, 2021) and it has received an increasing amount of academic attention in recent years (Zou, 2020). GBL is a mathematics teaching technique that creates a balance between classroom learning and educational games while enhancing the learning efficiency through student-centered learning activities (Lasut and Bawengan, 2020). It is also one of the more creative and entertaining methods, and, indirectly, students will pay attention to the teacher's lessons. This is due to the fact that playing games is innate to the students. Additionally, educational games may encourage the students to enjoy learning, to feel comfortable approaching a variety of difficulties along the way, and to overcome these challenges with focus, self-assurance, and patience, all of which are crucial for higher education in the development of lifelong learners (Liu et al., 2021).

This strategy is also founded in constructivist learning which emphasizes the importance of experiential learning through social interactions with the environment and their peers (Hourdequin et al., 2017). There is substantial data indicating that GBL is becoming increasingly popular as an effective learning approach utilized to create an engaging learning environment. On the basis of the empirical evidence from recent studies, the effectiveness of digital games in the education context has further proven the potential of GBL in boosting motivation, engagement, and social influences (Hernández-lara and Serradell-lopez, 2018).

According to Wong and Osman (2018), there are two types of game: digital and non-digital games. GBL, in the form of digital or non-digital games, aims to achieve the learning objectives set. According to Khairuddin and Mailok (2019), the GBL approach is used to stimulate and motivate the students to participate more actively in the learning process, to make the learning process more enjoyable, and to assist the students in comprehending the lessons more effectively. The GBL technique enables teachers to include active learning in their lessons, to increase the students' interest and engagement, and to receive instant feedback from the students' performance.

It should be noted that teachers should pay close attention to how gamification affects their student's interactions, emotionality, and cognitive activity—three aspects of the educational process. However, the acceptance and engagement of gamification in pedagogy remains challenging (Ding et al., 2018). The implementation of the gamification techniques is less appropriate to be carried out when the pupils have special needs (Mohamed Rosly and Khalid, 2017). This is due to the fact that the competence level of the pupil will affect the effectiveness of the implementation of gamification. In a general sense, this systematic literature review (SLR) was conducted to identify the influence on the cognitive and affective domains due to T&L Mathematics utilizing a game-based learning (GBL) approach.

1.1. The review protocol—PRISMA

This review was guided by PRISMA, developed by Page et al. (2021) with the aim of complete reporting to allow readers to assess the appropriateness of the methods used. In addition, presenting and summarizing the characteristics of the studies contributing to a synthesis allows policymakers to evaluate the applicability of the findings to their settings. A systematic review was chosen to describe, evaluate and synthesize the current empirical studies on the implications on the cognitive and affective domains of pupils due to game-based learning (GBL) methods in the teaching and learning of mathematics (T&L). Consideration was given to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement as a guideline to ensure that the research was conducted systematically (Moher et al., 2009).

1.2. Systematic search strategy

To find the relevant papers, there were four systematic techniques (identification, screening, eligibility, and included) used in this phase. The authors were able to completely discover and synthesize the research using these techniques, resulting in a well-organized and transparent systematic literature review.

Two databases, Scopus and Web of Science (WOS), were utilized for searching for previous research articles. The Scopus database is a library database that indexes the abstracts and citations of the scientific journal articles owned by Elsevier, a major journal publisher in the world offering high-impact papers. The Scopus database can be accessed through the off-campus access service for students provided by Tun Seri Lanang Library in the National University Malaysia *via* the website https://login.ezplib.ukm.my/menu. The Web of Science (WOS) database was chosen because it is an online digital library for research and educational information and a repository that specializes in the education field. Setting the appropriate keywords at this stage was essential for generating articles that met the study objectives.

1.2.1. Phase 1: Identification

"Influence of Game-Based Learning in Mathematics Education on the Students' Cognitive and Affective Domains" is the title of this study. This study's key contribution is its evaluation of the impact of game-based mathematics instructions on student cognitive and affective functioning. As a result, data from the Scopus and Web of Science (WOS) databases was used in this study, along with the keywords game or game-based, mathematics or math, and affective or domain. The researcher read the article titles and abstracts after conducting a keyword search to identify articles relevant to game-based learning in mathematical education. The identification phase revealed 353 articles from Scopus and 420 articles from the Web of Science (WOS) using the search items "gamification," "affective domain," and "mathematics" along with Open Access and fixed operators. The number of detected articles was 773 in total. Some duplicate articles across the two databases were detected and eliminated. Table 1 below shows the specific keywords used for the database.

1.2.2. Phase 2: Screening

The screening process occurred after identifying the articles. The articles were then either included or excluded from the study based on a specific set of criteria. The listed criteria were determined by the researchers (Mohamed Shaffril et al., 2021). The criteria considered for this study were adapted from several other SLR studies, namely the studies by Margot and Kettler (2019), Mohamed Shaffril et al. (2020), Mat and Mohd Matore (2020), and Amalina et al. (2021). The criteria that have been set were (i) articles published from 2018 to 2022, (ii) articles from journals only, (iii) articles related to the mathematics learning research field at the school level only, (iv) full-text articles, and (v) articles that have empirical data (Mat and Mohd Matore, 2020). It was carefully adapted to match the study requirements. The inclusion and exclusion criteria for this study are listed in Table 2.

Articles published prior to 2016, chapters from books and journals, review pieces, publications from proceedings, and articles written in languages other than English and Malay were among the 522 articles eliminated at this stage. The screening revealed a total of 251 items. Consequently, 39 articles that were identical between the two bases were found and eliminated, leaving a total of 212 articles.

1.2.3. Phase 3: Eligibility

Detailed information of each article was exported from both the databases and saved in the eligibility phase. Using the Mendeley Desktop software, each article was downloaded and examined. Article-related information such as the titles, researchers' names, journal names, and years of publication were cross-checked so then each piece of information was undoubted. The detailed information of each study was stored using the Microsoft 365 Excel software. Using this software, the study's abstract, country, purpose, activities, findings, and implications were extracted and documented. This method made it simpler to organize the findings according to the context of the study, alphabet, years, and country. In addition, the tabulated summary of the findings and charts was able to be easily incorporated into the text of this article. In conclusion, for the eligibility phase, 70 out of the initial 212 papers were ineligible for synthesis because they lacked empirical data.

1.2.4. Phase 4: Included

The initial search highlighted 23 document results from the Scopus database and 41 document results from the Web of Science (WOS) database. There was more research conducted on the 54 qualifying papers. Ultimately, 28 documents were chosen and properly examined. Figure 1 depicts a summary of the literature review's selection procedure.

2. Results

A total of 28 papers were chosen through a search and selection procedure based on the goal of this study and the stated study criteria. Table 3 shows all articles selected based on the author's name, year of publication, country, and article title.

2.1. Research background

The background analysis is based on 28 papers and includes the country, year of publication, type of approach, and the respondents' education level for each.

2.1.1. Countries

Twenty nations were involved in 28 articles. Six United States articles (Hulse et al., 2019; Ke, 2019; Moon and Ke, 2020; Ramani et al., 2020; Scalise et al., 2020; Thai et al., 2022), two articles from Spain (Jiménez et al., 2020; Zabala-Vargas et al., 2021), two articles from Greece (Altanis et al., 2018; Malliakas et al., 2021), two articles from South Africa (Delport, 2019; van Putten et al., 2020), and two articles from Taiwan (Yeh et al., 2019; Liu et al., 2021) were included. There was one article each from Australia (Vanbecelaere et al., 2020), China (Deng et al., 2020), Croatia (Juric et al., 2021), Finland (Kärki et al., 2021), Germany (Kiili et al., 2018), Hong Kong (Ting et al., 2019), Indonesia (Suryani et al., 2019), Ireland (Rocha and Dondio, 2021), Jordan (Al Khateeb, 2019; Baek and and Touati, 2020), Morocco (Tazouti et al., 2019), Portugal (Barros et al., 2020), Sweden (Alkhede and Holmqvist, 2021), and Turkey (Ilhan, 2021). Figure 2 shows the list of selected articles based on country.

2.1.2. Year of publication

In terms of publishing year, two articles were published in 2018 (Altanis et al., 2018; Kiili et al., 2018). In 2019, nine articles were published (Al Khateeb, 2019; Delport, 2019; Hulse et al., 2019; Ke, 2019; Suryani et al., 2019; Tazouti et al., 2019; Ting et al., 2019; Yeh et al., 2019; Rocha and Dondio, 2021). Subsequently, there were eight publications in 2020 (Baek and and Touati, 2020; Barros et al., 2020; Deng et al., 2020; Jiménez et al., 2020; Moon and Ke, 2020; Scalise et al., 2020; Vanbecelaere et al., 2020; Juric et al., 2021). Furthermore, there were eight articles (Alkhede and Holmqvist, 2021; Ilhan, 2021; Juric et al., 2021; Kärki et al., 2021; Liu et al., 2021; López et al., 2021; Malliakas et al., 2021; Zabala-Vargas et al., 2021) published in 2021. In 2022, there was only one article published (Thai et al., 2022). In summary, the majority of papers published in 2019 were chosen, followed by those published in 2020, 2021, 2018, and 2022. The list of selected articles based on year of publication is shown in Figure 3.

2.1.3. Research method

There were three sorts of research method used: qualitative, quantitative, and mixed. As shown in Figure 4, there were 20 quantitative studies where 72% specifically used a quantitative approach (Kiili et al., 2018; Al Khateeb, 2019; Delport, 2019; Hulse et al., 2019; Suryani et al., 2019; Tazouti et al., 2019;

TABLE 1 Specific keywords used for the databases.

Database	Website	Search key words
Scopus	https://www.scopus.com/home.uri	TITLE-ABS-KEY ((“game” OR “game-based”) AND (“mathematics” OR “math”) AND (“affective*” OR “domain*” OR “influence*”))
Web of Science (WOS)	https://www.webofscience.com/wos/woscc/basic-search	TS = ((“game” OR “game-based”) AND (“mathematics” OR “math”) AND (“affective*” OR “domain*” OR “influence*”))

TABLE 2 Article inclusion and exclusion criteria set.

Process	Selection limits	Included	Excluded
Criteria	Year	Articles starting 2018	Articles before 2018
	Type of publishing	Journal Articles	*Books, Proceedings of Conferences, Book Subtitles, Theses, Newspaper Clippings*
	Field of study	Mathematics learning	Apart from mathematics learning
	Access	Full access articles	Articles with limited access
	Type of research	Empirical data research	Non-empirical data research

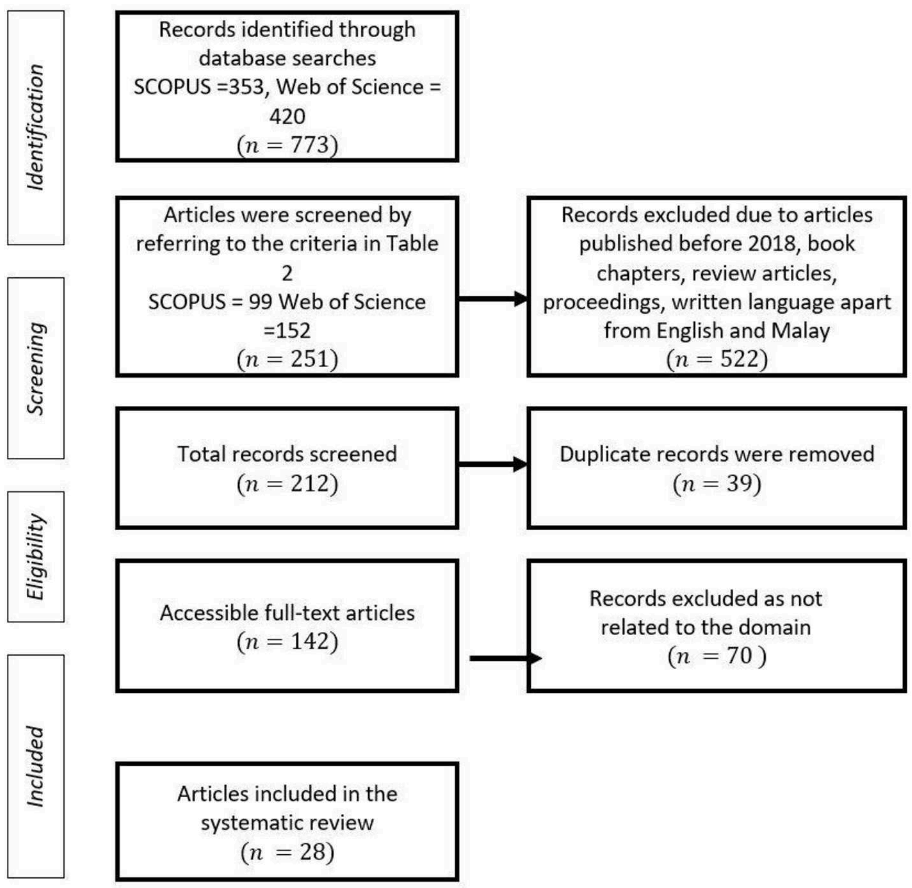

FIGURE 1
PRISMA systematics review adapted from Page et al. (2021).

Ting et al., 2019; Baek and and Touati, 2020; Barros et al., 2020; Jiménez et al., 2020; Ramani et al., 2020; Scalise et al., 2020; Vanbecelaere et al., 2020; Ilhan, 2021; Juric et al., 2021; Kärki et al., 2021; Liu et al., 2021; Malliakas et al., 2021; Zabala-Vargas et al., 2021; Thai et al., 2022). Six studies (21%) employed a mixed methods approach (Altanis et al., 2018; Ke, 2019; Yeh et al., 2019; Moon and Ke, 2020; Juric et al., 2021; Rocha and Dondio, 2021). Only two studies (7%) used a qualitative approach (Deng et al., 2020; Alkhede and Holmqvist, 2021).

TABLE 3 Twenty eight selected articles.

Author's name	Year	Country	Method	Article title
Al Khateeb (2019)	2019	Jordan	Quantitative	Effect of mobile gaming on mathematical achievement among 4th graders
Alkhede and Holmqvist (2021)	2021	Sweden	Qualitative	Preschool Children's Learning Opportunities Using Natural Numbers in Number Row Activities
Altanis et al. (2018)	2018	Greece	Mixed	Systematic design and rapid development of motion-based touchless games for enhancing students' thinking skills
Baek and and Touati (2020)	2020	Korea	Quantitative	Comparing Collaborative and Cooperative Gameplay for Academic and Gaming Achievements
Barros et al. (2020)	2020	Portuguese	Qualitative	The effect of the serious game Tempoly on learning arithmetic polynomial operations
Delport (2019)	2019	South Africa	Quantitative	Numeracy students' perspectives on a new digital learning tool at a South African university
Deng et al. (2020)	2020	China	Qualitative	Digital game-based learning in a Shanghai primary-school mathematics class: A case study
Hulse et al. (2019)	2019	United State	Quantitative	From here to there! Elementary: a game-based approach to developing number sense and early algebraic understanding
Ilhan (2021)	2021	Turkey	Quantitative	The Impact of Game-Based, Modeling, and Collaborative Learning Methods on the Achievements, Motivations, and Visual Mathematical Literacy Perceptions
Juric et al. (2021)	2021	Croatia	Quantitative	Motivational Elements in Computer Games for Learning Mathematics
Kärki et al. (2021)	2021	Finland	Quantitative	Improving rational number knowledge using the NanoRoboMath digital game
Ke (2019)	2019	United State	Mixed	Mathematical problem solving and learning in an architecture-themed epistemic game
Kiili et al. (2018)	2018	Germany	Quantitative	Evaluating the effectiveness of a game-based rational number training - In-game metrics as learning indicators
Liu et al. (2021)	2021	Taiwan	Quantitative	An Integrated View of Information Feedback, Game Quality, and Autonomous Motivation for Evaluating Game-Based Learning Effectiveness
Malliakas et al. (2021)	2021	Greece	Quantitative	Educational Intervention through a Board Game for the Teaching of Mathematics to Dyslexic Greek Students
Marín-Díaz et al. (2020)	2020	Spain	Quantitative	Digital escape room, using Genial.Ly and a breakout to learn algebra at secondary education level in Spain
Moon and Ke (2020)	2020	United State	Mixed	Exploring the Relationships Among Middle School Students' Peer Interactions, Task Efficiency, and Learning Engagement in Game-Based Learning
Ramani et al. (2020)	2021	United state	Quantitative	Racing dragons and remembering aliens: Benefits of playing number and working memory games on kindergartners' numerical knowledge
Rocha and Dondio (2021)	2019	Ireland	Quantitative	Effects of a videogame in math performance and anxiety in primary school
Scalise et al. (2020)	2020	United State	Quantitative	Benefits of Playing Numerical Card Games on Head Start Children's Mathematical Skills
Suryani et al. (2019)	2019	Indonesia	Quantitative	Pengaruh model pembelajaran teams games touraments dengan permainan monopoli terhadap hasil belajar matematik di SMK kolese tiara bangsa
Tazouti et al. (2019)	2019	Marocco	Quantitative	JeuTICE: An arabic serious game to enhance mathematics skills of young children
Thai et al. (2022)	2022	United State	Quantitative	Accelerating Early Math Learning with Research-Based Personalized Learning Games: A Cluster Randomized Controlled Trial
Ting et al. (2019)	2019	Hong Kong	Quantitative	Active learning via problem-based collaborative games in a large mathematics university course in Hong Kong
van Putten et al. (2020)	2020	South Africa	Mixed	The developmental influence of collaborative games in the Grade 6 mathematics classroom
Vanbecelaere et al. (2020)	2020	Australia	Quantitative	The effects of two digital educational games on cognitive and non-cognitive math and reading outcomes
Yeh et al. (2019)	2019	Taiwan	Quantitative	Enhancing achievement and interest in mathematics learning through Math-Island
Zabala-Vargas et al. (2021)	2021	Spain	Quantitative	Strengthening Motivation in the Mathematical Engineering Teaching Processes – A Proposal from Gamification and Game-Based Learning

2.1.4. Respondents

Students served as the respondents in the selected research studies. They were categorized as being involved in early education (Kindergarten and Preschool), primary school, secondary school (Middle School and High School), and university. Four studies involved early education students (Ramani et al., 2020; Scalise et al., 2020; Alkhede and Holmqvist, 2021; Thai et al., 2022). There were 12 studies involving lower school students (Kiili

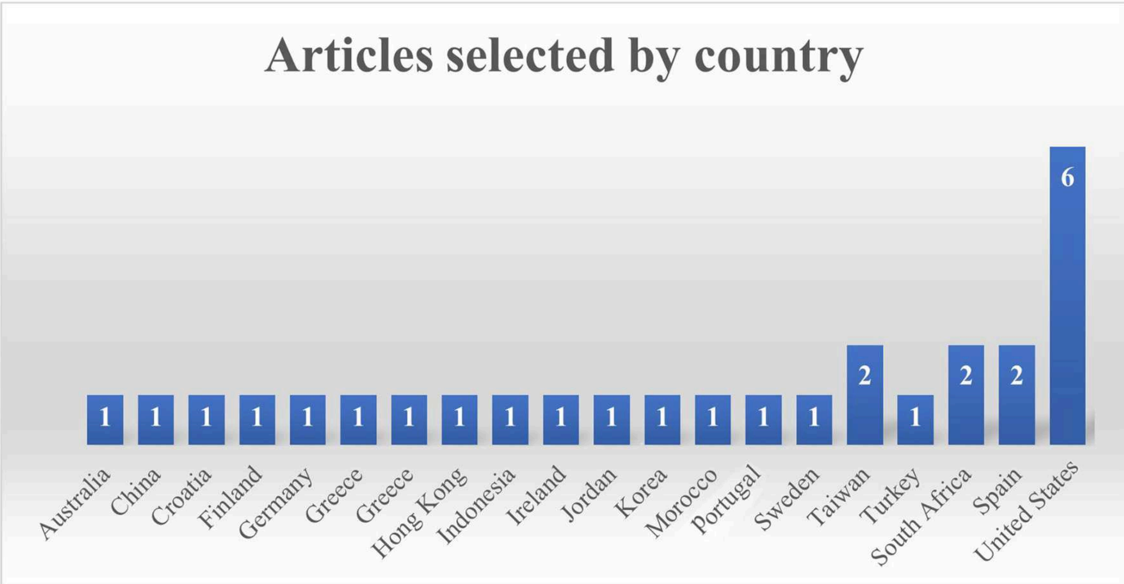

FIGURE 2
Number of articles based on country.

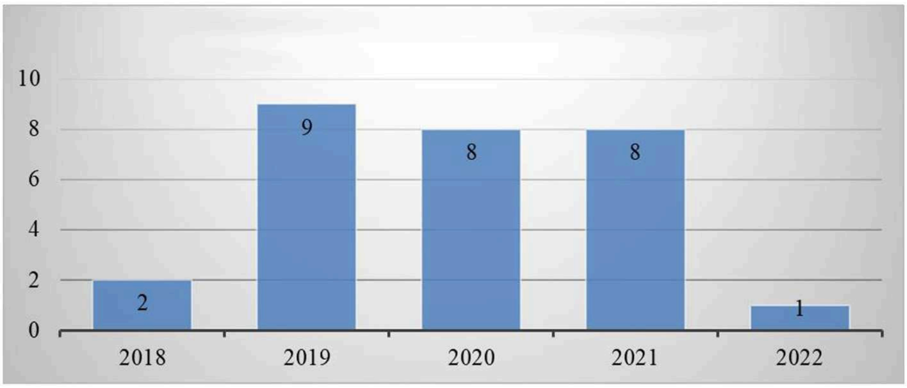

FIGURE 3
Number of articles based on year of publication.

et al., 2018; Al Khateeb, 2019; Hulse et al., 2019; Tazouti et al., 2019; Yeh et al., 2019; Baek and and Touati, 2020; Deng et al., 2020; Vanbecelaere et al., 2020; Ilhan, 2021; Juric et al., 2021; Kärki et al., 2021; Rocha and Dondio, 2021). Eight studies involved high school students (Altanis et al., 2018; Ke, 2019; Suryani et al., 2019; Barros et al., 2020; Jiménez et al., 2020; Moon and Ke, 2020; Juric et al., 2021; Malliakas et al., 2021). Only four studies involved university students (Delport, 2019; Ting et al., 2019; Liu et al., 2021; Zabala-Vargas et al., 2021). Figure 5 shows the number of articles based on the respondents' education level.

2.2. Contextual factors

The contextual factors consist of the mathematical topics examined, the types of game employed (digital or non-digital), and the programs or gaming instruments employed.

2.2.1. Mathematics topics studied

Several topics have been extensively blended with game-based learning (seven studies). For example, natural numbers (Alkhede and Holmqvist, 2021), rational numbers (Kiili et al., 2018; Kärki et al., 2021), numeracy (Delport, 2019), numerical skills (Vanbecelaere et al., 2020), and numerical and function skills (Ramani et al., 2020; Scalise et al., 2020). Three studies focused on geometry topics (Altanis et al., 2018; Moon and Ke, 2020; Ilhan, 2021). Three studies focused on algebra topics (Hulse et al., 2019; Barros et al., 2020; Marín-Díaz et al., 2020). Not only that but some studies focused on the topics involved in arithmetic (Yeh et al., 2019; Deng et al., 2020), calculus (Ting et al., 2019), and problem-solving (Ke, 2019). Ten studies focused only on mathematical knowledge and did not focus on specific topics (Al Khateeb, 2019; Suryani et al., 2019; Tazouti et al., 2019; Baek and and Touati, 2020; van Putten et al., 2020; Juric et al., 2021; Liu et al., 2021; Malliakas et al., 2021; Rocha and Dondio, 2021; Zabala-Vargas et al., 2021; Thai et al., 2022). Figure 6 shows the number of articles based on the topics studied.

2.2.2. Utilized game type (digital and non-digital)

There were 23 studies (82%) using digital game-based learning (Altanis et al., 2018; Kiili et al., 2018; Al Khateeb, 2019; Delport, 2019; Hulse et al., 2019; Ke, 2019; Tazouti et al., 2019; Ting et al., 2019; Yeh et al., 2019; Baek and and Touati, 2020; Barros et al., 2020; Deng et al., 2020; Marín-Díaz et al., 2020; Moon and Ke, 2020; Ramani et al., 2020; Vanbecelaere et al., 2020; Juric et al., 2021; Kärki et al., 2021; Rocha and Dondio, 2021; Zabala-Vargas et al., 2021; Thai et al., 2022). Only five studies (18%) employed non-digital games (Suryani et al., 2019; Scalise et al., 2020; Alkhede and Holmqvist, 2021; Juric et al., 2021; Malliakas et al., 2021). Figure 7 shows the number of articles by type of game used.

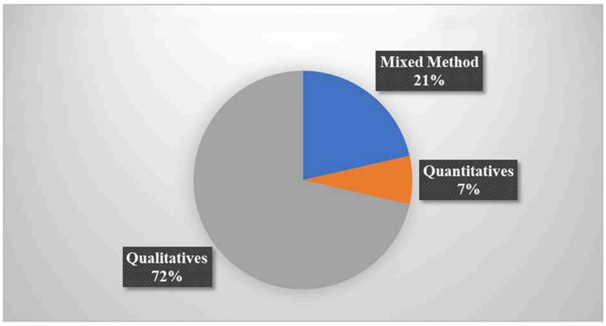

FIGURE 4
The number of articles based on the research method used.

2.2.3. Utilized application or educational game tool

There were 15 studies involving games with specific names, i.e., Serious Game Tempoly (Barros et al., 2020), Minecraft (Baek and and Touati, 2020), From Here to There (FH2T:E) (Hulse et al., 2019), Wuzzit Trouble (Deng et al., 2020), Mind Tap (Delport, 2019), Team Games Tournaments (TGT) with Monopoly (Suryani et al., 2019), My Math Academy (Thai et al., 2022), JEUTICE (Tazouti et al., 2019), NanoRoboMath (Kärki et al., 2021), Zagnonetke Mudrog Lisca (Juric et al., 2021), Kinect Game (Altanis et al., 2018), Digital Escape Room (Marín-Díaz et al., 2020), Once Upon a Maths (2D Game) (Rocha and Dondio, 2021), Math-Island System (Yeh et al., 2019), E- Rebuild (Moon and Ke, 2020), and an architecture-themed epistemic game (Ke, 2019). There were five studies stating games based on topics, namely rational number training in-game metrics (Kiili et al., 2018), number row activities (Alkhede and Holmqvist, 2021), geometry instruction activities (Ilhan, 2021), a Number Sense Game (NSG) and a Reading Game (RG) (Vanbecelaere et al., 2020), and numerical card games (Scalise et al., 2020). There were four studies looking into the type of games used, namely board games (Malliakas et al., 2021), digital games (Zabala-Vargas et al., 2021), mobile games (Al Khateeb, 2019), and tablet-based training games (Ramani et al., 2020). There were two studies stating games based on learning approaches, namely collaborative games (Ting et al., 2019; Juric et al., 2021). Table 4 shows the game applications and tools used in the previous studies.

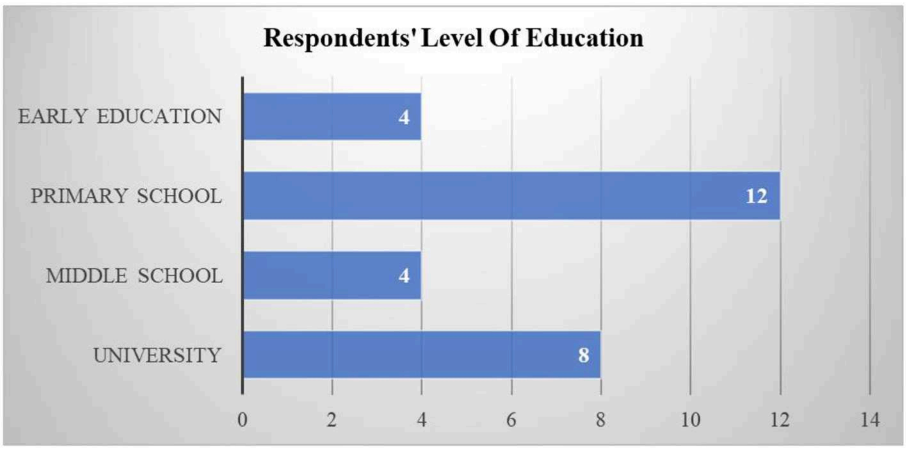

FIGURE 5
The number of articles based on the respondent's level of education.

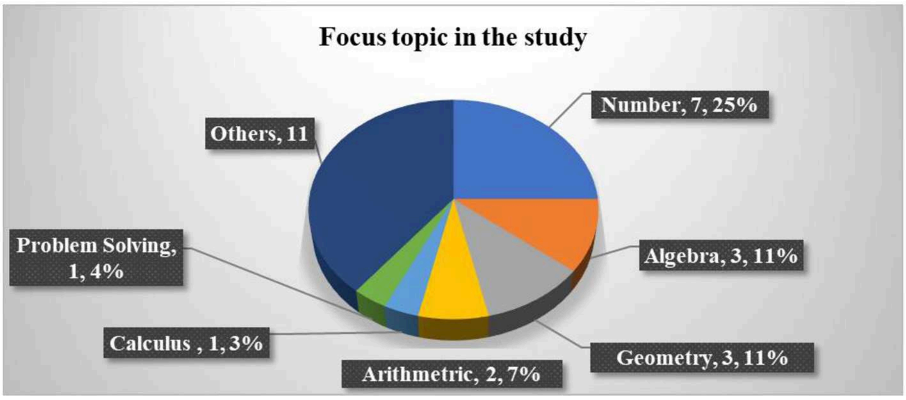

FIGURE 6
The number of articles based on the topic studied.

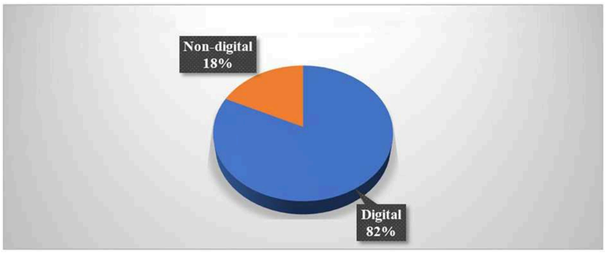

FIGURE 7
The number of articles based on the type of game used.

2.3. The developed theme

Learning is everywhere. Students learn mental skills, develop their attitudes, and acquire new physical skills as they perform the activities of daily living. Learning can be divided into three categories: cognitive, affective, and psychomotor. There are multiple levels of learning within each domain ranging from more basic, surface-level learning to more complex, deeper-level learning. The developed themes include the cognitive domain and affective domain. The cognitive taxonomy was described in 1956, and the affective taxonomy was described in 1964.

2.3.1. Cognitive domain

The cognitive domain aims to develop the mental skills and acquisition of knowledge of the individual. Mathematical performance implies a series of numerical and mathematical skills as well as certain general cognitive abilities that, if inadequate, can have a cascading effect on mathematical learning. Twenty-eight of the chosen research studies demonstrate that game-based learning generates favorable responses in the cognitive domains. The cognitive domains manifest in 27 studies, including knowledge, skills, and the students' achievement in mathematics. The cognitive domain relates to knowledge and intellectual skills such as understanding, organizing ideas, analyzing and synthesizing information, applying knowledge, choosing among alternatives in problem solving, and evaluating ideas or actions.

There were 20 studies involving knowledge, skills, and achievement (Altanis et al., 2018; Kiili et al., 2018; Al Khateeb, 2019; Delport, 2019; Hulse et al., 2019; Ke, 2019; Suryani et al., 2019; Tazouti et al., 2019; Ting et al., 2019; Yeh et al., 2019; Baek and and Touati, 2020; Barros et al., 2020; Jiménez et al., 2020; Ramani et al., 2020; Scalise et al., 2020; Vanbecelaere et al., 2020; Alkhede and Holmqvist, 2021; Juric et al., 2021; Kärki et al., 2021; Thai et al., 2022). There are numerous cognitive functions involved in learning mathematics. Processing speed can help with simple tasks like decoding numbers and counting quickly which can help with speeding up mathematical operations. When developing training, it is critical to consider the cognitive domain and its subcategories. Activities for teaching knowledge may differ significantly from those for developing cognitive abilities such as synthesis, application, and evaluation. When a researcher considers the cognitive subcategories, they should consider developing objectives that will help the participants advance through this learning process.

2.3.2. Affective domain

The affective domain is one of three domains in Bloom's taxonomy. The domain includes the manner in which people deal with things emotionally such as feeling, values, appreciation, enthusiasm, motivation, and attitudes. Gamification's main objectives are to improve certain skills, add learning objectives, engage students, optimize learning, support behavior changes, and to socialize. Twenty-eight of the selected articles have shown that game-based learning generates positive changes in the affective domains. The gamified learning approach has the potential to alter student behavior and is widely acknowledged as one of the most useful tools for creating intrinsically motivating experiences. A growing body of research demonstrates how digital games can foster and maintain high levels of learning motivation and engagement. Digital game-based learning (DGB) is thus increasingly recognized as an invaluable medium to promote emotionally engaging learning experiences. The most significant affective domain that appeared in the study is the motivation of the students when learning mathematics.

Table 5 shows the analysis of the previous studies on the cognitive and affective domains. There were a total of 20 studies

TABLE 4 Analysis of the previous studies regarding the application or game tools used.

No.	Education games	References	Remarks
1.	Serious game tempoly	Barros et al., 2020	Educational games with specific names
2.	Minecraft	Baek and and Touati, 2020	
3.	Form here to there (FH2T:E)	Hulse et al., 2019	
4.	Wuzzit trouble	Deng et al., 2020	
5.	My math academy	Thai et al., 2022	
6.	JEUTICE	Tazouti et al., 2019	
7.	NanoRoboMath	Kärki et al., 2021	
8.	Team games touraments (TGT) with monopoli	Suryani et al., 2019	
9.	Once upon a maths (2D game)	Rocha and Dondio, 2021	
10.	Math-island system	Yeh et al., 2019	
11.	Digital escape room	Marín-Díaz et al., 2020	
12.	Zagnonetke mudrog lisca	Juric et al., 2021	
13.	Kinect game	Altanis et al., 2018	
14.	Architecture-themed epistemic game	Ke, 2019	
15.	E-Rebuild	Moon and Ke, 2020	
16.	Rational number training in-game metrics	Kiili et al., 2018	Games based on mathematical topics
17.	Number sense game (NSG), reading game (RG)	Vanbecelaere et al., 2020	
18.	Number row activities	Alkhede and Holmqvist, 2021	
19.	Gometry instruction activitis	Ilhan, 2021	
20.	Numerical card games	Scalise et al., 2020	
21.	Mobile game	Al Khateeb, 2019	Games based on the type of game tools used
22.	Tablet-based training games	Ramani et al., 2020	
23.	Board game	Malliakas et al., 2021	
24.	Digital game	Zabala-Vargas et al., 2021	
25.	Collaborative games	van Putten et al., 2020	Game-based learning approach
26.	Collaborative game	Ting et al., 2019	

found involving the students' attitude, motivation, interest or involvement (Altanis et al., 2018; Kiili et al., 2018; Al Khateeb, 2019; Delport, 2019; Hulse et al., 2019; Ke, 2019; Tazouti et al., 2019; Yeh et al., 2019; Barros et al., 2020; Deng et al., 2020; Jiménez et al., 2020; Moon and Ke, 2020; Ramani et al., 2020; Alkhede and Holmqvist, 2021; Ilhan, 2021; Juric et al., 2021; Liu et al., 2021; Rocha and Dondio, 2021; Zabala-Vargas et al., 2021; Thai et al., 2022). In detail, there are six studies related to attitude and interest, eight studies related to motivation, and six studies that examine the students' involvement in their classes.

3. Discussion

3.1. Influence of game-based learning in mathematics education on the students' cognitive domain

According to the results of the systematic literature review, 14 of the identified studies were relevant to both the cognitive and affective domains. Five studies only focus on the affective domain, while one study focuses on the cognitive domain only. Game-based learning affects both the cognitive and affective domains. Game-based learning is a way of active teaching and learning that involves the use of commercial or educational games in the classroom. Engaging students in their learning, known as active learning, a learner-centered teaching strategy, calls for their participation in activities. To achieve a meaningful learning experience, these tasks include responding to inquiries, resolving issues, discussing the material, passing along knowledge, and externalizing cognitive processes (Yllana-Prieto et al., 2023). It is believed that identifying and implementing game elements in this process can improve learning across a variety of topics, domains, and fields of study (Alshammari, 2019). The findings of a systematic literature review show that 19 successfully identified studies are unquestionably associated with the cognitive domain. The cognitive domain involves knowledge and the development of mental or intellectual skills. There are six main categories of cognitive processes: knowledge, understanding, application, analysis, synthesis, and evaluation. The cognitive domain discusses the recollection or retention of knowledge and

TABLE 5 Analysis of the previous studies on the cognitive and affective domains.

No.	Domain	Cognitive domain			Affective domain			
	Author/domian	Mathematical knowledge	Mathematical skill	Achievement	Attitude	Motivation	Interest	Involvement
1	Kiili et al. (2018)	1		1	1			
2	Altanis et al. (2018)	1	1		1			
3	Ting et al. (2019)	1		1				
4	Al Khateeb (2019)			1				1
5	Yeh et al. (2019)	1		1			1	
6	Hulse et al. (2019)	1		1				1
7	Tazouti et al. (2019)	1		1		1	1	
8	Ke (2019)			1	1			1
9	Delport (2019)	1	1			1	1	1
10	Suryani et al. (2019)			1				
11	Scalise et al. (2020)		1	1				
12	Baek and and Touati (2020)			1	1			
13	Jiménez et al. (2020)	1				1		
14	Deng et al. (2020)						1	1
15	Moon and Ke (2020)							1
16	Ramani et al. (2020)	1			1			
17	van Putten et al. (2020)	1	1	1				
18	Barros et al. (2020)	1		1				1
19	Vanbecelaere et al. (2020)	1						
20	Liu et al. (2021)					1		
21	Malliakas et al. (2021)			1				
22	Rocha and Dondio (2021)			1		1		1
23	Kärki et al. (2021)	1		1				
24	Juric et al. (2021)				1	1		
25	Alkhede and Holmqvist (2021)	1					1	
26	Zabala-Vargas et al. (2021)					1		
27	Ilhan (2021)			1			1	
28	Thai et al. (2022)	1	1			1		

the development of intellectual abilities and skills. Cognitive objectives vary from readily recalling learned materials to combining and synthesizing new ideas and materials in original and creative ways. GBL helps to develop the learners' cognitive abilities, encourages problem-solving, facilitates collaboration, and raises self-esteem.

3.1.1. Knowledge and skills

Games are considered to be an effective tool in education for quickening learning, teaching challenging material, and encouraging systemic thinking (Ding et al., 2018). Numbers, algebra, geometry, arithmetic, calculus, problem-solving, and mathematical topics in general are covered. Students, including those in early education, primary school, secondary school, and university, can gain mathematical knowledge and skills through game-based learning. One of the most effective learning strategies is active learning through gamification which allows the students to learn through playing games and using their classes more effectively. Training groups using video games have significantly increased their conceptual and rational amount of knowledge (Mohd et al., 2020). For example, educational digital games use software that is able to improve the students' problem solving skills and the' lessons in mathematics (Acquah and Katz, 2020). Besides this, the use of digital game-based learning in mathematics learning has been found to help students improve their memory and understanding of learning and abstract mathematical concepts. In other words, DGBL can be a bridge to connect a concrete understanding with the students' abstract understanding of mathematics. This indirectly allows them to master the concrete steps for solving various mathematical problems. Through various DGBL applications where the mathematical lesson content is adjusted to fit the game, teachers can help their students formulate situations into mathematical forms, use concepts, facts, procedures, and reasoning, and interpret, apply, and evaluate mathematical results. In addition, the exciting visuals in the DGBL application can help maintain the students' attention and working memory toward the learning activities and further help the students speed up their visual information processing through the mathematical learning activities. Not only that, in high-level thinking skills, the use of digital game-based learning, such as educational mathematics games or simulation games, also impact the students' mathematical skills, primarily through the various reasoning tasks in DGBL mathematical activities. This matter is a central element when learning mathematics as it seeks to foster logical, critical, creative, innovative, and analytical thinking to better face various mathematical problems (Mahmud et al., 2021).

3.1.2. Achievement

Game-based learning has been shown to improve the students' achievements when learning. This is because this is a 21st-century learning style that stresses student-centered learning in which students learn collaboratively with their teachers and peers *via* conversations and problem-solving (Wong and Osman, 2018). The user-centered design allows the learning experiences to be psychologically accessible, not just physically. It also reflects the student's cognitive knowledge and socioemotional profile besides how their unique psychological attributes relate to the environment and pedagogical framework (Mahmud et al., 2022). However, it permits taking into account the fact that every student has unique needs that must be taken into consideration (Hernández-lara and Serradell-lopez, 2018). In addition to the incorporation of game-based learning into student education, the integration of mediated reality technology is viewed as a contributor to the students' achievements. Eighty-two percent of the research studies reviewed utilized digital games to teach mathematics. The merging of technology elements in the use of digital games as a student response system is one of the requirements that substantially stimulates the learning environment to become more engaging and significant (Bicen and Kocakoyun, 2018). This is consistent with the findings of Ding et al. (2018) who discovered that the achievement of their pupils increased when they incorporated digital games into the lesson. With the engagement of motivation, interest, attitude, and active involvement in studying mathematics through a game-based learning technique, the outcomes from the learning applications assist the students in comprehending their lesson content and ultimately enhancing their academic performance.

3.2. Influence of game-based learning in mathematics education on the students' affective domains

The affective domain refers to the affective reactions to a stimulus. According to research, game-based learning positively impacts on a students' affective domain in terms of attitude, motivation, involvement, interest, and confidence. In addition to the cognitive domain, appropriate tactics should take into account the affective domain such as the students' development stages, needs, abilities, talents, and interests so then the teaching and learning offered are more applicable and relevant (Ashikin and Roslinda, 2019). Besides this, mathematics learning activities through DGBL provide space for students to boost their engagement through collaborating and communicating during the learning activities which provides a good affective development space for students. There are various additional advantages of using DGBL in teaching and learning mathematics activities including socio-emotional and soft skills development. In addition, the development of the students' potential will also be increased through a positive competitive environment in DGBL-based learning activities that are conducted in a competitive manner. The healthy competition created in DGBL through progressive learning as part of the experience provides space for the students to accelerate their cognitive and emotional development, thereby increasing their self-efficacy toward learning mathematics (Mahmud et al., 2020).

3.2.1. Interest and motivation

Educational games improve interest and concentration, improving the students' learning (Alonso-Fernández et al., 2020). Games also stimulate motivation because of its impact on cognitive development, affective skills, and the emotional and social states of the students (Paravizo et al., 2018). A game-based learning environment can increase the students' interest and motivation. The findings indicate that employing a game-based strategy to create an engaging, dynamic environment can help children have fun while learning. As a result, teaching and learning sessions can boost the students' interest and motivation. Students can be indirectly exposed to the idea that learning is not solely dependent on the teacher's presentation in the classroom but that it can also take place in a more engaging and effective way when they are on their own (Jasni et al., 2019). The advantages of game-based learning include accommodating the students' interests and motivation. In addition, teaching games that encourage the students to acquire greater goal orientation through increased patience, repeated learning, teamwork, and friendly rivalry during the learning process is also beneficial (Ding et al., 2018). Both variables aid the students in their attempts to comprehend and master the subjects presented, particularly mathematics. Subramaniam et al. (2022) explained that the subject of mathematics is often considered to be a difficult and boring subject. This has indirectly reduced the students' motivation and interest in learning mathematics. However, based on DGBL features that can attract the students' interest such as goals, rules, competition, challenge, fantasy, and entertainment, it is possible to provide added value and new initiatives as part of increasing the students' motivation and interest in learning mathematics (Mahmud and Law, 2022). In addition, using DGBL in mathematics learning that is carried out collaboratively has a more significant impact on the student motivation toward learning than collaborative learning activities that do not use DGBL applications. In addition, using visual rewards in the DGBL application, such as badges and tokens, also serve as a method of positive reinforcement to increase the students' interest and motivation in mathematics.

3.2.2. Engagement

Engagement is a different behavioral attitude that has been found to be a useful indicator of academic performance while being positively correlated with student learning outcomes (Delfino, 2019). Students are encouraged to achieve exceptional results when learning through digital games because it is unquestionably more enjoyable. Engagement happens when someone's attention is completely focused on a specific activity. Thus, the virtual games industry indicates that engagement is a tool to keep the player's attention on the game. The method used in game-based learning is a student-centered method that requires the students' active participation throughout the lesson. This method allows the students to experience playing while learning which is more enjoyable than traditional learning methods that cause the pupils to become bored (Rebollo et al., 2022). The implementation of learning methods based on digital games can grab the students' attention, motivate them to engage themselves with learning, and raise their achievement levels (Tangkui and Keong, 2020). This game-based learning method does not require the students to be static in their respective places, only focusing on the whiteboard in front of them. This can help the teachers create a conducive and cheerful atmosphere during the teaching and learning process. In addition to being a requirement for successful educational practices, engagement can also be defined as the time and effort that students devote to their academic pursuits. There are three components to it: affection, cognition, and behavior. One teaching and learning strategy that aims to boost student engagement and make lessons more interesting is called "gamification in education" (Nisa et al., 2020). Through game-based learning activities, students can interact with digital learning materials and engage more dynamically in a fun learning environment. This is because game-based learning emphasizes the development and use of games as a tool in learning while playing and helps the teachers design lessons more interactively to help the students understand mathematical concepts in an advanced manner. This will indirectly increase the level of student engagement to help them focus on learning mathematics.

3.2.3. Attitude

Game-based learning affects knowledge gains in addition to mathematical accomplishments. However, affective factors like the students' attitudes and beliefs about mathematics and its teaching are also crucial components of mathematics education because they can have a significant impact on the students' mathematical abilities and future mathematic learning (Vankúš, 2021). Attitude toward mathematics is defined as a liking or disliking of mathematics, a tendency to engage in or avoid mathematics activities, a belief that one is good or bad at mathematics and a belief that mathematics is useful or useless (Kurniasih et al., 2020). Game-based learning can make students more creative and focus better on their studies, facilitating the learning process with their friends, encouraging collaborative behavior through problem-solving, and maintaining the students' interest in the learning process (Khairuddin and Mailok, 2019). The findings of the study by Sahin and Yilmaz (2020) also proves that the use of games has a favorable and significant impact on the academic achievement and attitude of pupils. With the help of games, students gain a deeper understanding of abstract topics through 3D virtual objects with the aid of video games to achieve more meaningful learning. Based on their research, they also discovered that the students were satisfied and wished to continue using augmented reality in the future. Furthermore, game-based learning elements that emphasize competition and learning while playing makes the learning more enjoyable for the students and reduces their anxiety about math subjects. This indirectly assists the students in developing social-emotional growth and soft skills (Baul and Mahmud, 2021). Furthermore, the use of DGBL can catalyze the students' levels of self-efficacy when solving various mathematical problems through various challenging learning experience activities, as well as improving the students' social skills and communication confidence in various collaborative learning environments.

4. Conclusion

In conclusion, this systematic literature has analyzed 28 articles regarding the influence of game-based learning on the cognitive and affective domains of students from 2018 to 2022. Since 2019, the number of studies relating to game-based learning has increased.

In this case, the limited working memory of the students may point to a particular challenge, specifically remembering information and carrying out manipulations or operations at the same time. Thus, the use of GBL can help the students learn effectively and finish the task given in a manner that is linked to normal short-term memory. The entertainment element in GBL leads the student to learning and studying with enthusiasm. Students can even finish the task given which requires the passive repetition of elements.

Besides, the effectiveness of learning mathematics differs depending on the learning environment. As such, the use of GBL, which promotes an environment that combines game content with knowledge, will enhance the students' learning progress. The integration of the student's cognitive and affective domains with GBL can also support the learning process which creates an easier yet powerful enough environment for the students to study in.

Exploring new ways of learning through the implementation of GBL also benefits the students according to their cognitive and affective domains. Well-designed and correctly utilized GBL can improve the student's learning due to the competitive elements which encourages the students to engage in learning mathematics. The impact of the rewards act as a motivation and can also attract the student's interest in learning, especially in relation to their cognitive aspect.

However, the teachers faced difficulties when it came to inventing personal gamification tools based on the student's different mathematical knowledge in order to cater to their needs. In this case, the teachers had to allocate plenty of time to engage in the planning and designing of gamification tools. Even if this is possible, the teaching preparation and concern about the effectiveness of the learning makes the situation unwise for teacher to distribute their time according to.

The factors that influence the cognitive and affective domains of the students when they are learning are essential. Therefore, GBL should be implemented successfully in the teaching and learning of mathematics because it is said to be an excellent platform to improve learning. In short, this research proves that game-based learning is being increasingly acknowledged and incorporated in T&L. The cognitive and affective domains are used to classify diverse items. The research instruments employed, the selection of the research participants, and the game design regarding the influence of game-based learning are recommended for use in future studies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MM conceived, designed, collected the database, organized the database, and performed the analysis for the study. HH managed data collection ethics, co-wrote the manuscript, and contributed to manuscript revision. All authors read and approved the final submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The use of oral questioning to improve students' reasoning skills in primary school mathematics learning

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Reasoning skills are essential mathematical skills that need to be taught to students starting in primary school and have even become the main domain in global assessments such as TIMSS and PISA. Therefore, this study aimed to explore the implementation of the use of oral questioning in improving students' reasoning skills in mathematics at the primary school level. Data for the qualitative case study were collected through semi-structured interviews, observations, and field notes. Six mathematics teachers from six different primary schools were selected as participants in the study using the purposive sampling method. The data were then analyzed using a constant comparative method to identify the patterns and themes that emerged. The study found six types of oral questions that are identified as being used by mathematics teachers to help students improve their mathematical reasoning skills and thinking, namely, provocative mathematical questions, puzzle-shaped questions, breaking down hard problems into easier parts, contextual questions, questions to explain the mistakes, and questions asking for clarification. The findings showed that primary mathematics teachers used a variety of oral questions to help students develop their mathematical reasoning skills and, at the same time, assist them in developing higher order thinking skills. This research has implications for expanding the literature and understanding of how primary school teachers perceive that using certain oral questions can help improve students' mathematical reasoning. In addition, the study's results revealed the importance of oral questioning in teaching mathematical reasoning skills.

KEYWORDS

oral questions, reasoning skills, primary school, mathematics teaching, mathematics learning

1. Introduction

Mathematical reasoning is a critical skill that entails analyzing and evaluating mathematical statements or hypotheses without regard for context or meaning (Mueller et al., 2014). It is a mathematical concept that allows students to determine the truth values of given statements. Mathematical reasoning enables people to solve math problems without using algorithms or predefined processes (Curriculum Development Division, 2019). It entails applying logical and critical thinking to a mathematical problem to make connections and determine the best solution (Steen, 1999). Mathematical reasoning is an essential foundation for understanding mathematics more effectively and meaningfully. The development of mathematical reasoning is closely related to students' intellectual and communication development. Reasoning can develop logical thinking and even increase the capacity for critical thinking, which is the basis of understanding mathematics profoundly and meaningfully (Payadnya, 2019). Therefore, teachers need to provide space and opportunity by designing teaching and learning activities that require students to do mathematics and be actively involved in discussing ideas in mathematics.

Mathematical reasoning is a fundamental part of the education system in many countries. For instance, the Common Core State Standards for Mathematics in the United States emphasize the importance of mathematical reasoning and problem-solving skills. In the United States, mathematical reasoning tends to focus on problem-solving and the application of mathematical concepts to real-life situations. The education system encourages students to think critically, analyze data, and communicate mathematical ideas effectively (Resnick et al., 2023). The National Curriculum for Mathematics in the United Kingdom also focuses on developing mathematical reasoning and problem-solving skills (Jones et al., 2004). Mathematical reasoning is taught in Japan using a problem-solving approach that emphasizes visual aids and real-life scenarios. In Japan, mathematical reasoning emphasizes the importance of visual representations in understanding mathematical concepts, such as diagrams and graphs. Students are encouraged to think creatively and solve problems through trial and error (Fujita et al., 2022).

Mathematical reasoning is an essential skill that needs to be applied by teachers in mathematics teaching activities to ensure that students' thinking can be improved (Morsanyi et al., 2018). Mastery of reasoning skills by students allows them to understand abstract mathematical concepts. Furthermore, it assists students in solving various mathematical problems, particularly non-routine mathematical problems, by employing various logical and creative solution methods. Therefore, the Malaysian Ministry of Education, through the Mathematical Curriculum Framework that was introduced, has emphasized the importance of mastering mathematical reasoning skills to form students' mathematical thinking because it involves the process of creating mental associations and thinking in increasingly complex ways, a process which develops students' mathematical reasoning abilities and takes time and ongoing effort (Ministry of Education Malaysia, 2014). Moreover, it allows students to deal with increasing amounts of simultaneity in order to help the brain build a complex web of connections. Therefore, mathematical reasoning is an essential foundation for students to understand the content of learning mathematics more effectively, in addition to fostering understanding related to the knowledge of mathematics in a more meaningful way (Mahmud et al., 2020b).

Issues related to the level of reasoning skills possessed by students, as well as students' weaknesses in applying reasoning skills in mathematics learning activities and solving various non-routine problems, need to be given attention because this issue is also linked to mathematical achievement in the Global TIMMS assessment where the average score obtained is still below the minimum level (Ministry of Education Malaysia, 2020). This is because the issues of the questions found in the TIMMS global assessment focus very much on aspects of students' thinking and reasoning skills. For example, suppose students have low levels of thinking and reasoning skills. In that case, students will find it challenging to plan various solutions to various mathematical problems where the importance of applying skills is expressed. Hence the importance of mastering reasoning skills such as problem-solving, analytical thinking, inductive and deductive reasoning, and creative thinking for students because mathematical reasoning is closely related to developing a student's intellect and communication. Applying good reasoning skills can develop logical thinking capacity and even increase critical thinking capacity, which is also the basis for a deep and meaningful understanding of mathematics (Mahmud, 2019). Therefore, to achieve this goal, students should be trained and guided to constantly provide logical explanations and analyze, judge, evaluate, and justify all mathematical activities. In addition, teachers need to provide space and opportunities for mathematical discussions that are not only engaging but allow each student to be involved.

In an effort to improve students' reasoning skills in mathematics in the process of teaching one of the techniques that can be used is to use effective oral questioning (Mahmud et al., 2019). The teacher's oral questioning as a teaching strategy can stimulate students' thinking and enable the teacher to understand the level of student achievement in addition to allowing students to explain their understanding (Çelik and Güzel, 2016). In addition, teachers can use oral questioning to challenge and elicit students' thoughts, increasing students' curiosity, and interest in a topic being taught (Rini et al., 2020). The teacher's oral questioning practice in the mathematics teaching process allows students to get ideas and strengthen them through their speech and writing.

However, teachers must diversify strategies, techniques, and levels of oral questioning (higher-order or lower-order) to suit the students' conditions and needs (Johar et al., 2017). The teacher's ability to practice effective questioning skills and strategies is an essential element in the effort to instill and apply thinking skills, and it is an art that needs to be mastered and practiced (Curriculum Development Division, 2016).

The use of high-order questioning techniques is seen as a more effective questioning technique to enhance students' critical thinking than low-order questioning, which only focuses on knowledge and understanding (Larson and Lovelace, 2013). This is very important because higher-order thinking skills (HOTS) is one of the six main features emphasized by the government through the Malaysian Education Development Plan (PPPM) 2013–2025. This is in line with the findings of (Mahmud, 2019), which stated that emphasis should be placed on the quality of questions teachers ask and not the quantity, i.e., a large number of teacher questions does not reflect the teacher as a better questioner, and it also does not help in improving students' high-level thinking (Hassan et al., 2016). In their study, they also found that the most frequently used strategy for teaching with elements of HOTS is questioning. Therefore, to ensure that oral questions improve student learning, teachers should use the appropriate level of questions so that the teaching objectives can be achieved. Gaspard (2013) stated that there are two levels of questions that teachers often use in their teaching activities, namely, low-level and high-level questions. Using high-level questioning skills by teachers through questions in the form of problem-solving can open up space for in-depth discussion, encourage exploration, and increase student involvement in the teaching process (Mahmud et al., 2020a). The implementation of good oral questioning does not only focus on high-level questions but also needs to be diversified according to circumstances and situations although (Hassan et al., 2016) it has been suggested that teachers need to focus on using high-level questions. Mirza (2018) explains that teachers need to diversify their level of questioning to equip students with clearer mathematical senses and thinking. Therefore, teachers should diversify the level of oral questioning in the class in a balanced manner and in accordance with the learning objectives so that the learning process becomes more meaningful (McAninch, 2015).

Mullis et al. (2016) in the TIMSS 2015 results report for mathematics subjects, it was reported that Malaysia experienced a decrease in scores obtained from 1999 to 2011. Still, there was a slight increase in mathematics achievement in Shahrill and Clarke (2014) stated that one of the causes of the decline in the performance of students in Malaysia in the TIMSS global assessment is the lack of oral questioning activities that can stimulate students' reasoning in the mathematics teaching process. Students found it difficult to understand the questions used in the TIMSS test, which focuses more on exploratory questions where students not only have to remember and understand mathematical facts but also make connections between the knowledge they have and make explicit judgments about solving a mathematical problem. Students' weaknesses in reasoning aspects also contribute to students' weaknesses in understanding abstract mathematical concepts, making justifications, and analyzing and translating mathematical problems that require higher-level thinking and reasoning skills (Wong, 2015). Not only that, but ineffective oral questioning makes it difficult for students to argue and defend their solution to a mathematical problem.

It is possible that the type of oral questions asked by the teacher is not appropriate, so the understanding of mathematical concepts is too complex for students to master and cannot improve the level of students' thinking in learning mathematics (Kaya et al., 2014). Studies (Belcher, 2016) show that teachers are more fond of asking convergent questions than divergent-type questions that can elicit students' thinking. The use of convergent questions causes students' thinking not to diverge and not to develop (Subramaniam et al., 2022). This also indirectly affects the level of students' reasoning because their thinking is less trained to think creatively and critically, thus causing students' reasoning skills to be affected. The correct use of oral questions can help students improve their ability to reason logically and present arguments honestly and convincingly. This is because mathematics is a science based on well-defined objects and concepts that can be analyzed and transformed in various ways using "mathematical reasoning" to reach certain and timeless conclusions.

Thus, in planning oral questions that can help students improve their mathematical reasoning, there are six key understandings proposed by PISA 2022 to provide structure and support for mathematical reasoning. These key insights are:

1. Understanding quantity, number systems, and their algebraic properties.
2. Understanding the influence of symbolic representation and abstraction.
3. Recognizing regularities in mathematical structures.
4. Recognizing functional relationships between quantities.
5. Using mathematical modeling to view problems from the real world (such as those from the physical, biological, social, economic, and behavioral sciences).
6. Realizing that variation is the core of statistics.

In addition, mathematics teachers are more fond of using only low or medium-cognitive level questions and focus less on high-cognitive-level questioning, causing the mathematics teaching activities that are implemented to be less stimulating and provoking to students' thinking (Mahmud et al., 2022). Low-level questions in this context refers to questions that focus on specific details or facts within a mathematical concept or problem such as "What is the formula for finding the perimeter of a rectangle" and "What is the square root of 64?" (Hauser, 2017) stated that this happens because a lack of knowledge and skills in oral questioning among mathematics teachers makes it challenging to construct high-level questions in mathematics teaching.

Past studies report that one of the issues or problems that students often face while learning mathematics in mathematics class is difficulty solving math problems (Setiyani et al., 2020; Pazin et al., 2022). It has been explained that this happens because of the lack of effective oral questioning activities implemented to train and improve students' mathematical reasoning skills. Students' weaknesses in the reasoning aspect contribute to students' weaknesses in understanding abstract mathematical concepts, making justifications, and analyzing and translating mathematical problems that require higher-level thinking and reasoning skills (Morsanyi et al., 2018). Not only that, the result of ineffective oral questioning also makes it difficult for students to argue for and defend the solution to a mathematical problem.

However, little is known about how primary school mathematics teachers use oral questioning to improve students' reasoning skills in mathematics, particularly when it comes to the types of questions used in primary school mathematics instruction (Mahmud et al., 2020a). In addition, the absence of a framework for the implementation of oral questioning specifically related to the teaching of mathematics in primary schools in the context of education in Malaysia requires this study to be carried out to help create a deeper understanding of the implementation of the use of oral questioning in improving students' reasoning skills in mathematics at primary school. Thus, this study is expected to show the real scenario of how oral questioning practices are implemented by primary school mathematics teachers so that the problems that arise can be identified and then solved through some suggested solutions.

2. Methodology

This is a qualitative study that uses multiple case study methods. The selection of this method meets the research question that needs to be answered because the case study allows for a comprehensive overview and a complete and deep understanding related to the implementation of oral questioning in mathematics teaching in primary school.

Six primary schools in a district in Negeri Sembilan have been selected as venues for research to explore and understand the teacher's oral questioning practices in the teaching process of applied mathematics. The selection of this district as a study location is based on Marshall and Rossman (2014) argument that the characteristics of the place to conduct the study should be easy to enter, there should be no obstacles to conducting research, there should be a high chance of collecting in-depth data, there should be freedom of research, and it should be easy for participants to participate in the study.

A total of six outstanding primary school mathematics teachers from six different schools have been selected as study participants by using the purposive sampling method. The selection of research participants for this study is based on criteria and characteristics determined by the researcher, who is a mathematics option teacher teaching mathematics subjects at primary school, the excellent teachers who received appointments from the Ministry of Education Malaysia and the teacher are willing to be involved in this study. Based on the data, it is difficult for the researcher to obtain participants' studies according to the criteria set in the same school. Thus the participants' studies had to be selected from different schools.

While conducting the actual study, the researcher gave the participants a letter of acknowledgment and consent to be a study participant (informed consent) to be signed by the participant. This acknowledgement is an ethical requirement in research that needs to be obtained voluntarily from the study participants to avoid elements of coercion, deception, pressure, and any influence (Mahmud, 2019). Furthermore, this letter can provide additional protection for researchers in the event of legal issues. In addition to that, the researcher has also obtained permission to conduct the study from the Education Policy Planning and Research Division (BPPDP) of the Ministry of Education Malaysia and the State Department of Education to ensure that all research activities meet all the ethical standards that have been set in addition to ensuring better implementation of the study.

For data collection methods, the researcher used observation, interviews, and field notes. Using various data collection techniques can help researchers make data triangulation and strengthen the results obtained (Miles et al., 2014). The non-participatory observation process was carried out according to the actual teaching schedule of the study participants. The observation process is carried out using an observation protocol adapted from a previous study (Ling and Mahmud, 2023). The number of observations carried out depends on the topic taught and the level of data saturation obtained by the researcher. The process of making observations is done consecutively for each study participant. This procedure will indirectly increase the validity and reliability of research findings (Miles et al., 2014). The mathematics teaching process was observed to see the implementation of oral questioning recorded using a video recorder to obtain information and to get a more comprehensive picture of the behavior of study participants during the teaching process. During the observation process, the researcher took written field notes that provide information about the classroom that cannot be seen through audio recordings and transcripts and other matters related to the aspects studied. For example, field notes contain information about students, the classroom environment, the overall atmosphere in the school that may affect the teacher in making decisions, and information about student behavior as well as notes about what the teacher presents that are not recorded, such as examples written or shown on the whiteboard.

As for the interview method, two interview sessions were conducted for each study participant, namely, an initial interview and a stimulated-recall interview. The first session was an initial interview that contained questions on the teacher's philosophy for teaching, the teacher's philosophy on questioning, the classroom environment, and the roles of the teacher and students during class discussions. The interview protocol for this initial interview was adapted from the interview protocol built by Mahmud et al. (2020b). The second interview session was a stimulated-recall interview, a more specific and in-depth interview based on observations (Iksan and Daniel, 2015). The second interview session contained questions about the decisions made by the teacher during the mathematics teaching process. In conducting this second interview, the researcher adopted the interview protocol developed in a previous study (McAninch, 2015). This interview is also a reflection on the instructions that were followed. In addition, the document used for analysis is the record book of the daily teaching plan, which contains a daily plan for each teacher's teaching session in mathematics subjects.

The data obtained were analyzed using the constant comparative analysis method by the researcher himself to see patterns and themes contained in the data obtained, where this data is primary (Kolb, 2012). The constant-comparison analysis is focused on qualitative research to see the similarities and differences of each theme. This is a data coding process where the data is broken down to be filtered and then interpreted in a meaningful way to build a theme. There were three stages of coding in the data analysis process: open coding, axial coding, and selective coding. Similar themes are grouped in a category, and this comparison will continue until the data reach saturation (Marshall and Rossman, 2014). In this context, saturation refers to a situation where the researcher feels that there is no longer any new data or information obtained to support the theme and information to the researcher from three data sources, namely, observation, interviews, and field notes. The first stage of data analysis is open coding, breaking down, examining, comparing, conceptualizing, and categorizing data. This process aims to collect as many themes and categories as possible related to the study phenomenon and to identify categories related to the theoretical foundation. The researcher reads the data several times before creating tentative labels for pieces that summarize what is happening, not based on existing theories but only on the meaning that emerges from the data. The researcher obtained preliminary concepts, categories, characteristics, and dimensions at this open coding stage. As a result, the researcher identifies and categorizes categories based on emerging themes.

The following stage is the axial coding process, in which the data is reorganized in a new way after open coding by connecting categories. This is accomplished through a coding paradigm involving situations, contexts, action/interaction strategies, and their consequences. According to Corbin et al. (2014), the main emphasis of axial coding is constantly asking questions and making comparisons, as well as inductive and deductive thought processes related to subcategories to categories. It is critical to verify the details of a category to see the relationship between the categories and explain the relationship between them. During this process, the researcher reads the verbatim data repeatedly, attempting to identify passages or sentences that provide an idea of the studied issue and are relevant to answering the research question. If a quote has the same meaning or description of the same category, then the quote is coded into the category that has been created. Yin (2013) mentions that this process is known as pattern matching, where the coded sentences are based on existing categories. However, if the found sentence does not match the existing category, a new category must be formed. This process continues until no more new categories can be formed.

The final stage is the selective coding process, which is a process of identifying and selecting core categories, systematically linking them with other categories, verifying similarities and relationships, and then settling on categories that may need to be further refined or developed. During this selective coding process, the categories and their relationships are combined to form a "storyline" that describes "what is happening" in the phenomenon being studied and answers the research question.

In this study, the researcher used several methods to increase the validity and reliability of the study, including the triangulation method, an audit trail, and long periods in the field. To ensure the reliability of the research findings, this study also used an analysis of Cohen Kappa to measure agreement between raters for the themes and subthemes obtained in this research. In this study, the data were verified by two expert raters in Mathematics Education who are lecturers in mathematics education at two leading universities in Malaysia and a district education officer skilled in mathematics education pedagogy. The Cohen Kappa coefficient (κ) is a statistic that measures agreement between raters for qualitative items (categories). Cohen Kappa analysis also refers to finding the reliability of the unit of analysis from verbatim qualitative data and is also known as inter-rater reliability. The importance of inter-rater reliability lies in the extent to which the data collected in the study can truly represent the variable being measured. McHugh (2012) stated that this analysis can also determine the extent to which the selected analysis unit can accurately describe the themes that arise from the interviews and directed to the questions to be studied. Thus, the Cohen Kappa Index analysis aims to find the degree of agreement between experts on the unit of analysis with the theme or construct being studied (Wilhelm et al., 2018).

Therefore, once all the data has been processed and the themes of the research findings have been produced, the researcher prepares a set of expert consent forms to evaluate the themes created. This is important to ensure high reliability for each find to describe a theme (Landis and Koch, 1977). It was stated that a Kappa coefficient value that exceeds 0.75 is the best agreement above 50 per cent of expected agreement, a value of 0.40–0.75 is a moderate value above the expected percentage of agreement, and a value of 0.40 and below is weak because the value is below 50 per cent expected approval. Thus, the agreement value experts on the theme successfully produced in this study are $K = 0.89$, which is very good.

3. Findings

The findings of this study have identified and classified several types of oral questions used by the study participants throughout their teaching, where the questions are used to help improve students' reasoning skills in mathematics. In this study, there are six types of oral questions that math teachers can use to help students improve their mathematical reasoning and thinking. These are provocative mathematical questions, puzzle-shaped questions, questions that help students break down hard problems into easier parts, questions about the context, questions that ask students to explain their mistakes, and questions that ask for clarification.

In this study, the researcher used pseudonyms to represent each participant to protect the confidentiality of participants. Each discussion of research findings is supported by excerpts from the teacher's observation, interviews conducted, and field notes. An example of a label for observation is (Azah, P3/12452–12723) where "Azah" is the name of the study participant, "P3" is the third observation for Teacher Azah, and "12452–12723" (is he position of the sentence in the analyzed teaching transcript document). Then for the interview transcripts, the researcher used the label "SRI" or "II" where "SRI" refers to the reflective teaching interview while "II" refers to the initial interview. For example, the label (Roza, SRI3/4751–5047) refers to "Roza," which the name of the study participant, "SRI3," which the third teaching reflective interview for Teacher Roza, and "4751–5047," which refers to the position of the sentence in the transcript document. In addition, for data involving field notes, the researcher uses the "NL" label such as (Ada, NL/17082022) where "Ada" is the study participant name, NL the field note, and "17082022" the date of the field note, which is August 17, 2022.

3.1. Provocative mathematical questions

The study found that participants used provocative questions at the beginning of the mathematics teaching session. Provocative questions are said to challenge students' thinking, check the intellectual level of potential employees, and even be used to encourage students to think more actively. In the following interview excerpt, Teacher Ada discusses the significance of using provocative questioning:

> *"As mathematics teachers, we need to constantly provoke students' thinking to improve their reasoning skills. With this, students can challenge their thinking and find creative and logical solutions without relying on the mathematical solution procedures they usually use."*

(Ada, SRI2/34212–34557).

Not only that, but Teacher Ada also explained that, when the teacher asks provocative questions, the teacher needs to challenge the students to prove their answers mathematically: *"We also need to challenge them so that they can prove their answers through logical solutions but cannot run away from the actual concepts of mathematics"* (Ada, SRI2/34212–34557). The excerpt below shows the provocative questions asked by the participants in the mathematics teachneacher Nadia explained that throughig session:

> *Teacher Okay, I have a question for you all to think about. Please listen carefully. The question is, Cindy wants to buy a*

> *lollipop priced at RM 0.70. Name the coin that Cindy can use to pay for the lollipop.*
> *Student Let me try, teacher! (Students raise their hands to answer the question).*
> *Teacher Ok, good, please.*
> *Student 20 cents and 50 cents, so we get 70 cents.*
> *Teacher Yes, it's good. Is there anything else?*
> *Student Let me try: 20 cents plus 20 cents plus 20 cents and 10 cents.*
> *Teacher Yes, good, Ahmad.*

(Raha, P2/32114–33001).

The teaching excerpt above shows Teacher Raha trying to provoke students' thinking through questions that ask students to think of various solutions to the questions asked. This is an important effort that teachers must implement so that students' thinking is more divergent, and they can think of various creative solutions. In addition, provocative questions are also used to change students' perspectives and misconceptions about mathematical concepts. Teacher Nadia explains this in the following interview excerpt:

> *"When a teacher asks a question that makes you think, it's usually because the student's view or understanding of a mathematical concept is too narrow or because they don't know how the concept applies to the real world. So, through students' provocative questions, students' ideas about a mathematical concept are seen to be broader."*

(Nadia, SRI2/34212–34557).

In addition, the study's findings through observation found that provocative oral questions encourage discussions and arguments among students, causing the discussion of a topic to become more in-depth (Roza, P2/11175–11314). Therefore, this indirectly develops and improves students' reasoning skills and understanding of mathematics. This matter was also explained by Teacher Roza in the interview excerpt as follows:

> *"When the teacher gives provocative questions to the students, the discussion activity becomes more lively, and the session of exchanging opinions and finding ideas will certainly happen more actively. Then the students will use their reasoning skills to get various logical solutions."*

(Roza, SRI 3/23132–23997).

3.2. Puzzle-shaped questions

The study also found that teachers rarely ask questions directly but more often ask questions in the form of riddles or puzzles. In addition, the researcher's observation found that students are more active in thinking and finding solutions when the teacher asks questions in the form of puzzles (Ada, NL, 20092022). Teacher Ada also explains this in the following excerpt from the interview:

> *"I prefer asking mathematical questions in the form of puzzles because students seem more responsive to such questions. Students are also more active in thinking and enjoying themselves, so they are more active in finding answers to those questions."*

(Ada, SR1/3, 34514–35110).

The interview excerpt above explains that the questions asked in the form of puzzles are more interesting to students, and they prefer to think to solve the questions given to them. In addition, Teacher Ana thinks that the questions asked in the form of riddles encourage more discussion and student interaction, thus improving students' reasoning skills as a result of their discussion on the question. Teacher Ana explains this in the following interview excerpt:

> *"The questions asked in the form of puzzles increase students' interest in thinking and encourage more growth related to logical thinking because they will try to see the patterns that may exist on how to solve the puzzle questions and find more diverse solutions. In addition, they will sometimes think about and discuss among themselves the real purpose of the question and how to solve it."*

(Ana, SRI 1/36617–40012).

The excerpt above explains that questions asked in the form of puzzles will encourage students to think more through their logical thinking to understand a situation and the ideas found in the questions asked. Not only that, but the lively discussion that comes from talking about the puzzle question will also help students think more logically when solving math problems.

The questions asked in the form of puzzles also help students create beneficial habits of mind, such as persistence, thoroughness, creativity in solution-finding, and improved self-monitoring. Teacher Ana explains this in the following interview excerpt:

When we ask a question in the form of a puzzle, students are usually more interested in answering the question, so when students are interested, they will be more persistent, earnest, and thorough in trying to find a solution to the question. They will try various ways, according to their creativity, to get answers. *"With this, students' thinking will be more directed and stimulated to think more creatively to get answers"* (Ana, SRI 2/32114–33101).

In addition, the findings of the study also found that teachers also use "what if" questions to encourage students' mathematical reasoning. The excerpt below shows an example of how Teacher Nadia uses provocative questions in the form of "what if" in teaching mathematics:

> *"What would happen if I added 4 cm to the length of this rectangle?"*

(Nadia, P2/32114–33101).

> *"If eggs are $0.12 a dozen, how many eggs can you get for a dollar?"*

(Azah, P3/31345–31426).

Based on the excerpt above, teachers Nadia and Azah asked students a "what if" question to help them relate the new information found in the teacher's oral question and then draw a conclusion based on the previous situation. This allows students to strengthen the formation of strong conceptual relationships and further build their logical thinking skills.

3.3. Questions that break down hard problems into easier questions

Next, the teacher gives questions that break down hard problems into easier questions, almost the same as the original questions the teacher asks the students in mathematics teaching. Easier questions are asked to the students when the teacher finds that they cannot answer the questions asked to give them an idea about the operational procedures that the students need to do in answering math questions (Roza, NL, 23082022). The following excerpt demonstrates how students can be given questions that break down difficult problems into easier parts:

> *Teacher Now convert mm to cm. A total of 59 mm equal to how many cm?*
> *Student . . . (student is silent without any answer).*
> *Teacher Ok, question. Please listen. A total of 20 mm, how many cm?*
> *Student 2 cm.*
> *Teacher How do you get 2 cm?*
> *Students divide by 10.*
> *Teacher How do you divide 10? Ok, 20 divided by 10 gets 2 cm. This question is also the same.*

(Roza, P1/10375–10414).

Teacher Roza initially asked a slightly complex question about how to convert 59 mm to cm. However, the question did not get a response from the students, causing Teacher Roza to use a simpler question where she tried to reduce the numbers and use even numbers to help students understand the concept of unit conversion. Teacher Roza explained that this is intended to help students understand the mathematical concepts discussed more easily (Roza, SRI 3/19407–19708). Teacher Raha also said, *"Yes, we will use a slightly smaller number, but still in the same situation. This is intended to give them an understanding first because this big number will be a bit overwhelming"* (Raha, II, 19956–20138).

Teacher Azah also said, *"Maybe we will give an example with a small number so that the student can see what he has to do first"* (Azah, SRI 2/2816–3129). In addition, there are situations when the teacher needs to change the situation or "storyline" found in the questions asked to a problem close to the student's environment to help the student understand the question being discussed better. Teacher Ada explains this matter thus: *"Sometimes we need to change the situation in the question to a simpler one so that the students can see what the question wants"* (Ada, SRI 2/32009–32352).

Teacher Ada also added that when the students have successfully answered the easier questions, then the teacher can link back to the understanding the students have gained from the original, more complex questions. In this context, students' understanding is strengthened by responding to easier questions progressively before moving on to more complex questions (Ada, NL, 20092022). This is explained in the following excerpt from the interview: *"Yes. simplify the question first and then relate it to the original question that was a little difficult earlier. Step by step from easy to hard"* (Ada, SRI 1/34917–35403).

Therefore, easier questions given by the teacher as feedback are a form of continuous guidance from the teacher to help students think about and understand the mathematical concepts learned. In this context, the teacher tries to give an easier picture of the problem through smaller numbers, simpler operations, or simpler situations to help students connect with the original, more complex problem. With this, the teaching process can be carried out in an advanced manner.

3.4. Contextual questions

The findings of the study also found that teachers use questions based on mathematical modeling. This involves using mathematical concepts to solve real-world problems, providing students with a practical application for the math they are learning. Questions using mathematical modeling help apply mathematics in real-life situations, keeping students engaged and helping them develop deeper mathematical reasoning and critical thinking skills. Using questions based on mathematical modeling allows teachers to help students improve the acquisition and application of mathematical concepts and skills in a wider variety of situations, especially situations related to real-world problems. Here are some examples of contextual questions that can promote reasoning skills in mathematics provided by mathematics teachers in this study.

> *"A bus goes from a supermarket to the park at a constant speed of 70 km/h and returns to the supermarket at a constant speed of 80 km/h. What is the average speed of the bus for the entire trip?"*

(Roza, P3/3765–3912).

> *"A recipe for butter cookies calls for 4 cups of flour, 2 cups of sugar, and 2 cups of butter. If you want to make half of the recipe, how much of each ingredient will you need?"*

(Nadia, P3/1785–1982).

Teacher Nadia explained that through oral questions often associated with various situations in everyday life, students can use multiple mathematical concepts that have been learned and then apply them in various situations in their lives. *"I often give questions related to real-life situations, and then I will encourage students to think logically and creatively by using the mathematical concepts they have learned"* (Nadia, SRI3/20010–20214). Contextual questions give pupils an opportunity to see how the mathematical ideas they are learning are used in real-world situations. Students are better able to comprehend and remember the ideas when they can see how the math can be used in real-world scenarios.

In addition, Teacher Ana also gave her opinion on the oral questions given through the application of mathematical modeling, which she thinks can encourage or give students opportunities for various activities that can improve students' logical thinking through discussion, exploration, and experimentation. Working together on a contextual question can help students share ideas and develop their reasoning skills through discussion and debate.

This can indirectly improve students' mathematical reasoning while providing a good foundation for improving their problem-solving skills.

In addition, the study also found that encouraging questions related to the visualization of real-world problems can boost students' reasoning skills, whereas questions related to the visualization of the real world can provide more explicit ideas and guidance for finding solutions to mathematical problems. Teacher Ada explains this in the following interview excerpt:

> *"If we want to encourage reasoning skills, we need to ask questions to help students visualize the real world. This is because most learning ideas are linked to real-life situations. Through visualization of the real world, students will be able to make logical connections related to mathematical concepts more easily."*

(Ada, SRI 2/31119–31412).

Based on the quote above, Teacher Ada explained that oral questions related to the visualization of the real world provide support for students' logical thinking by helping them relate thoughts to the real world. The teacher also explained that through oral questions that use visualization of situations associated with the real world, it is important that students acquire the ability to represent real-world problems in mathematical terms and construct models to solve the issues. When students are engaged in modeling, their ways of thinking do not manifest as a single, one-dimensional sequence but instead as a series of cycles in which their mental models representing the given situation are expressed, tested, and revised. In other words, knowledge develops along multiple dimensions, from comparing to contrasting, from concretizing to abstracting, from specific to general, from simple to complex, or from a collection of uncoordinated, immature ideas to more coordinated, mature, and practical knowledge.

3.5. Questions to explain mistakes

The study also found that teachers give questions in the form of corrections to students' inaccurate or wrong answers. The teacher provides corrective questions to correct students' misconceptions and misunderstandings of the mathematical concepts learned. The following is an example of how corrective explanatory questions are applied in mathematics teaching:

> *Teacher How do you do it if you want to change meters to kilometers?*
> *Students multiply by 100.*
> *Teacher Is it true?!*
> *Students . . . (Student remains silent without giving an answer).*
> *Teacher Actually, you need to divide by 1000 because 1-kilometer equals 1000 m. So, we divide 4075 m by 1000.*

(Ana, P 3/11006–11140).

> *Student "3.7 cm × 10 = 37 mm" (The student writes on the whiteboard in the usual form, but there is an error in the calculation method).*
> *Teacher Alright. The first one does not have this amount of cm when multiplied by ten. You don't have to write this in cm because you want to change it to mm. This 10 is in mm.*

(Roza, P3/4293–4445).

The quote above shows how teachers give students corrective and explanatory questions during the mathematics teaching process. For example, teacher Ana corrected the students' misconceptions about the operation required to change the meter unit to kilometers. The answer given by the student is wrong, so Teacher Ana immediately corrects the mistake made by the student by providing the correct answer, and explaining to the student the right answer. Similarly, Teacher Roza gave feedback and corrective explanations about the inaccurate calculation procedures shown by the students on the whiteboard. Therefore, not only can the student's answers be corrected, but also when the teacher gives explanations as a form of correction, the students will have the opportunity to understand and correct their thinking on the concept being studied, as explained by Teacher Ada in the interview excerpt below:

> "Yes, correcting the answer he gave. Sometimes it's inaccurate because some are right and some are wrong, so we will tell you which is right, and which is wrong. Then, explain back to the students. So, they will better understand what is being studied."

(Ada, SRI 2/21268–21633).

Teachers also give students questions related to corrective explanations to help students understand why they are wrong and how they can learn from the mistakes they make. Teacher Ana explains this in the following interview excerpt:

> *"Being able to assist students in understanding why they are incorrect and learning from their mistakes."*

(Ana, II/22662–22843).

Therefore, the questions asked with corrective explanations allow the teacher to correct the student's answers through the explanations provided and allow students to correct their misunderstandings of the concepts learned. This makes them think from different points of view to figure out why they made mistakes.

3.6. Questions asking for clarification

The results of the observation of the teaching carried out by each study participant also found that the study participants used questions asking for clarification to guide and clarify the thinking of the students' reasoning as well as explore the origin of the students' thinking toward understanding the content of the lessons presented. Here is an example of how teachers use questions to ask for clarification in teaching mathematics:

> *Students 15 m (students answer the teacher's questions).*
> *Teacher How do you get the answer to 15 m?*
> *Students Multiply1.5 m by 10 to get 15 m.*
> *Teacher Ok good, so we got 15 m.*

(Roza, P 2/3049–3422).

> *Teacher How do you want to find MR, RS, and SN?*
> *Students Divide by 3.*
> *Teacher How do you know to divide by 3?*
> *Students Because there are three parts.*

(Nadia, P 1/9672–9831).

The researcher found that teachers use clarifying questions to ask students to explain how they got their answers, which in turn can help students strengthen their understanding and thinking about the topic being discussed. Teacher Roza stated that by asking students to explain their answers, they will better understand the content of the discussion and help the teacher assess the level of learning that the students have achieved.

> *"When we ask students to explain their answers, the students will definitely remember and understand what they are learning." In addition, it can allow teachers to assess the level of student understanding.*

(Roza, SRI 3/1166–1400).

Teacher Raha gave the opinion that questions asking for clarification also allow other students to benefit from the explanations provided by their friends. This indirectly helps other students understand the content of the lesson being discussed. Thus, he explained, *"Other students will also benefit and can help strengthen their understanding of the topic being studied"* (Raha, SRI 3/1438–1846). Teacher Ada also expressed the same opinion as Teacher Raha, where questions asking for clarification will help improve other students' understanding of the lesson's content (Ada, SRI 2/16129–16272).

Therefore, questions asking for clarification are used by teachers to help students clarify their understanding of and thinking on the content of the lesson being discussed. As a result, students can think more deeply and explain their understanding of the topic being discussed.

4. Discussion

The findings of the study have shown that the mathematics teachers in this study believe the use of certain oral questions can help improve students' mathematical reasoning. The use of various types of oral questions allows students to indirectly stimulate their sense of thinking and use stimuli extensively to generate inference and critical reasoning skills (Mahmud and Law, 2022). As a result, it is the teacher's responsibility to guarantee that the oral questions utilized are not only for remembering and learning mathematical facts but also for applying oral questions in the areas of analysis, synthesis, and assessment to raise thinking to a higher level.

The study found that mathematics teachers use provocative questions to encourage students' reasoning skills in mathematics. Oral questions like this can also increase students' creativity by encouraging them to think more creatively to find various alternative solutions to solving mathematical problems (Subramaniam et al., 2022). Developing ideas creatively is critical to helping students build mathematical skills and increase student inquiry in the context of learning mathematics. Therefore, provocative questions can encourage students to investigate, explore, collect data, draw conclusions to solve problems, reflect on the methods used, make observations, and communicate to share findings about the problem. In addition, provocative questions are also found to improve students' reasoning skills through the discussions that occur after the teacher asks provocative questions. In this context, students can learn to discuss and work mathematically. Students learn to talk and work mathematically by participating in mathematical discussions, proposing and defending arguments, and responding to the ideas and conjectures of their peers. The design and posing of thought-provoking tasks lead to such discussions, leading to a culture of justification and proof (Mueller et al., 2014). Not only that, but through active discussion, students will be able to use the correct mathematical language and apply logical reasoning.

In addition, teachers were also found to ask questions in the form of puzzles to improve students' mathematical reasoning skills. This finding is consistent with the findings of Douglas et al. (2006), who found that puzzle questions can help students develop mathematical reasoning skills. The use of oral questions in mathematics teaching in the form of puzzles provides a platform for learning mathematics that is more fun and indirectly increases students' interest in mathematics learning activities. When students' interest can be increased, they will voluntarily increase their efforts in finding solutions to the questions asked (Mahmud et al., 2020a). With this, students' thinking, and logical reasoning skills can be improved because their mental activity becomes more active in thinking creatively. Furthermore, when asked a question in the form of a puzzle, students will be taught to see patterns and methods of trying to succeed, and they will be given the opportunity to hypothesize the probability of solving a mathematical problem. Therefore, they will also have the chance to improve their ability to make judgments and decisions based on valid reasons and evidence until they can solve the puzzle question. With this, students' mathematical reasoning skills will always be trained and strengthened through active thinking and decision-making activities.

In addition, the study also found that to help students, especially low-achieving students, improve their reasoning skills, mathematics teachers were also found to break the questions down into simpler parts. This happened when students could not answer the questions posed by the teacher. The purpose of questions like this is to help students restructure their thinking and the mathematical concepts they have learned in accordance with the nature of the question. So, with this, students' thinking will be more organized and further develop students' logical thinking capacity to solve mathematical problems (Pazin et al., 2022). Questions can also be given using simpler questions, but they need to be given in the same context to help students understand the content and the required mathematical solution procedures. In this context, students' thinking will be directed toward planning real solutions to the mathematical problems presented to them and finding them relevant enough to be implemented in low-achieving classes to ensure continuous involvement and interaction from students. This indirectly ensures that the oral questions asked by the teacher can be given according to the suitability and actual abilities of the students (Mahmud and Law, 2022). In addition, this method is an advanced approach that can help students' understanding of the mathematical concepts discussed, as stated in Gagne's Instructional Theory.

In addition, the study also found that teachers ask contextual oral questions or involve mathematical modeling. Mathematical modeling is the process of describing a real-world problem in mathematical terms, usually in the form of equations, and then using these equations both to help understand the original problem and discover new features. In this context, reasoning skills are applied by solving problems related to real life by using knowledge from various disciplines.

A variety of unconventional solution contexts are generated through student thinking using new contextual situations outside the classroom to encourage students to think more deeply and not just recall what was learned in the classroom (MdYunus, 2015). Therefore, this allows students to relate the knowledge gained in the classroom to real life and further develop numeracy skills, reasoning skills, ways of thinking, and problem-solving skills through learning and mathematical applications so that, finally, students can use mathematics to describe the physical world.

In addition, it was found that the teacher also provided corrective explanatory questions to correct students' misconceptions about the mathematical concepts discussed. In this context, the teacher not only tells the students that the response given is wrong but also explains why the answer given is wrong. Giving correction questions in the form of explanations is crucial to helping students correct their understanding and allow them to self-reflect on the mistakes they have made while also assisting them in improving their learning and better organizing their mathematical problem-solving strategies (Shute, 2008). With this, students' reasoning skills will be trained, which will help them build confidence in determining the answers to the questions asked by the teacher.

However, the researcher believes corrective explanation questions should be given according to the situation and the student's ability level. This indirectly supports Gagne's theory of instruction, which emphasizes that the teaching that is planned or implemented should consider the level of student ability so that the implemented teaching process can meet students' various learning needs (Driscoll, 2000). As a result, it is critical to assist students in relating their mistakes to the teacher's corrective, explanatory feedback to modify their understanding to a correct understanding of mathematics (Mahmud and Yunus, 2018). Furthermore, this indirectly encourages students to make a logical analysis to determine the correct mathematical concept and strengthens students' reasoning skills.

It was also observed that teachers ask questions in which they ask students to clarify or expand on their answers. In this context, the teacher asks the students to think again and provide justification for their answers. This is important to ensure that students understand the response they give to the questions asked and to prevent them from answering questions carelessly without thinking or guessing the answer. Thus, by providing questions to ask for clarification from students, it can encourage high-level thinking and communicative competence such as explaining, argumentation, and justification, as well as being a necessity for students to participate in meaningful and authentic conversation and teaching exchanges between students and teachers (Evans, 2020). In addition, questions asking for clarification also help students clarify their ideas and thoughts, encourage the skills of justification and evidence, and allow students to use their existing knowledge in solving various problems. This can strengthen students' conceptual understanding in addition to helping them assimilate and accommodate their original knowledge.

5. Conclusion

Overall, this study has sought to expand the research literature by providing a deeper understanding of how oral questions aid the development of student reasoning in the mathematics teaching process. Mathematics teachers can use various types of oral questions to help improve students' logical reasoning skills in teaching mathematics. However, a mathematics teacher should be creative and dynamic in determining the types of questions that need to be used as a tool to develop students' mathematical reasoning skills (Johari et al., 2022). Reasoning is an essential foundation for understanding mathematics more effectively and meaningfully; thus, the oral questions used by teachers during mathematics teaching activities should consider the various needs of the student's environment, such as the student's ability level, the learning environment, and the available learning resources. To achieve this objective, the oral questions asked by the teacher during mathematics teaching should allow students to be trained and guided to make conjectures, prove conjectures, provide logical explanations, analyze, make judgments, evaluate, and provide justification for all mathematical activities. In addition, teachers need to provide space and opportunities for mathematical discussions that are not only engaging but allow each student to be involved.

Overall, this study greatly expands the literature, especially to researchers in the field of mathematics education, about how the use of oral questioning can help improve students' abilities in mathematical reasoning. In addition, the information in this study also gives implications to mathematics teachers, especially pre-service teachers in mathematics education, in understanding the diversity of methods that can be used to build students' mathematical reasoning skills. Finally, the study has obtained extensive qualitative data regarding the phenomenon of oral questioning in the mathematics teaching process, which is implemented to improve students' reasoning skills in mathematics. However, the findings of this study cannot be generalized to other populations. Therefore, a quantitative study should determine whether the findings can be generalized to other populations.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Educational Planning and Research Division (EPRD), Ministry of Education Malaysia. The patients/participants provided their written informed consent to participate in this study.

Author contributions

MM conceived and designed the study, collected and organized the database, and performed the analysis. MM and NM wrote the manuscript and contributed to manuscript revision. Both authors read and approved the final submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Does the psychoemotional well-being of Spanish students influence their mathematical literacy? An evidence from PISA 2018

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Data from international studies reveal that the mathematics literacy of Spanish students is significantly lower than that of students from nearby countries. Therefore, in recent years, interest in identifying the factors that influence students' mathematics results in Spain has grown considerably. Often, these factors are sought among the socioeconomic characteristics of the students or among variables related to the schools, ignoring the psychological and emotional factors of the students. This paper analyzes the impact of certain psychoemotional characteristics of Spanish students on their literacy in mathematics. For this purpose, multilevel regression models are applied to the data of the Spanish sample of the 2018 edition of PISA (Programme for International Student Assessment), which is composed of 35,943 15-year-old students. The instruments for data collection are the mathematics literacy tests and the contextual questionnaires on students' personal situation and well-being used by PISA. As dependent variable, students' mathematics literacy has been considered, measured through the plausible values provided by PISA, and as independent variables, different indices measuring students' psychoemotional well-being obtained from the contextual information collected by PISA. Results indicate that resilience, motivation for the achievement of learning objectives, competitiveness, perceived cooperation at school, and social connectedness with parents have a positive impact on students' mathematics literacy, while experiences related to bullying, physical self-concept, meaning in life and perceived competitiveness at school have a negative impact.

KEYWORDS

psychoemotional status, PISA, assessment, multilevel analysis, mathematical literacy

1. Introduction

It is widely found that the subject of Mathematics often stands out as being one of the subjects in which students tend to most under-perform (Gamboa Araya, 2014). In Spain, this assertion in supported by the findings of studies with international reach, such as those of the TIMSS (Trends in Mathematics and Science Study) and the PISA (Programme for International Student Assessment). Indeed, Mathematics results for Spanish students are in line with data produced by these studies and are found to be lower than those obtained by students from the majority of surrounding countries (Ministry of Education and Professional Training, 2019, 2020). Consequently, in recent years, interest in better understanding the potential factors to influence Mathematics literacy in Spanish students has grown significantly within the educational community with the aim of addressing this issue. In an attempt to identify these factors, studies have mainly focused on cognitive variables in relation to students (González-Pienda, 2003). This is due, in part, to the tendency to hold cognitive aspects in higher regard than all other aspects when it comes to educational processes (Fernández-Berrocal and Ruiz, 2008; García-Retana, 2012). Nonetheless, since the end of the last century, work such as that conducted by Salovey and Mayer (1990), Gardner (1995), Goleman (1996), and Bar-On (1997) began to highlight the importance of emotions in learning. Thanks to this, consideration of the emotional dimension has become more and more importance in educational processes. Such is this the case that some authors have urged the need to broaden the traditional understanding of intelligence to make room for psychological and emotional qualities, which differ from and, yet, complement cognitive capacities (Dueñas-Buey, 2002). In fact, it has even been suggested that students acquire certain emotional skills prior to gaining access to traditional academic material (Jiménez and López-Zafra, 2009).

The effects of the psychological and emotional state of students on their academic outcomes has been broadly documented in existing literature on different educational stages (Extremera-Pacheco and Fernández-Berrocal, 2004; Robles-Ojeda et al., 2011; Ferragut and Fierro, 2012; Ros-Morente et al., 2017). In general terms, the majority of conducted studies have highlighted that negative emotional states can have unfavourable repercussions on student learning processes and, consequently, their academic results, whilst the presence of good emotional well-being promotes efficient cognitive processes (Elizondo-Moreno et al., 2018).

The complexity of a student's psychoemotional status makes it difficult to study it directly. For this reason, the concept has been approached in a number of ways based on determined indicators or components that are easier to address. The components of a student's psychoemotional health can be classified as personal or relational. According to Perpiñán (2013), the former pertains to components that are related with understanding and control inherent to the student themselves, whilst the latter refer to the relationship and interaction of the student with individuals. Existing scientific literature does not reveal any clear consensus regarding the influence of individual components, such as aspects including perceptions of physical appearance, resilience, assertiveness, perseverance, self-esteem or stress management, of academic outcomes. Indeed, of the individual variables analysed by Broc (2019), only the management of stress was found to make a significant contribution towards explaining academic results in a group of secondary school students. Along the same lines, whilst Ruíz-Melero et al. (2020) reported evidence that stress management significantly correlated with student achievement in subjects from four different ambits (linguistic, scientific, social and artistic), other individual skills, such as self-esteem and assertiveness, only correlated with results in subjects that were artistic in nature but not in all other examined ambits. In contrast to these findings, a study conducted by Buenrostro-Guerrero et al. (2012) concluded that both stress management in students and their personal emotional abilities were found to be significantly related with performance at school. With regards to the relational component of psychoemotional health, it can be inferred that the emotional state of students is not only influenced by them themselves but is also conditioned by agents outside of their social setting. Of all of these agents, family, in general, and parents, in particular, play a central role in the emotional development of students. Family makes up the first social network of all individuals and constitutes a context charged with emotions that undoubtedly influences emotional development, especially during the stages of childhood and adolescence, and has repercussions in all ambits of life (Pichardo-Martínez et al., 2002; Orcasita-Pineda and Uribe-Rodríguez, 2010; García-Navarro, 2011; Márquez Cervantes and Gaeta González, 2017). With regards to the academic setting, parental involvement in their children's school development fosters positive attitudes and perceptions towards school in their children, which lead to improved academic performance of students (Jungert et al., 2020). In this line, authors such as Sánchez and Dávila (2022) and Lastre Meza et al. (2018) have highlighted that solid emotional accompaniment of parents to their children promotes their child's academic success. Finally, another aspect that influences an individual's emotional well-being refers to the experiences at the school. The school is a place not only for academic training, but also for personal and social development where a student spends a large part of the day (Kleinkorres et al., 2023). Authors such as Ryan and Deci (2020) point out that aspects such as confidence, self-esteem and mental health are profoundly affected by school students' experiences in their school. As a consequence, the concept of school well-being has recently emerged and has been studied by several authors, most of whom agree in including aspects related to students' affect and emotions derived from their experiences at school when defining it (Aulia et al., 2020). These experiences are strongly conditioned by the climate perceived to be present in the classroom and at the educational institution. In fact, the school climate has been found to be directly related with academic performance in students, with this relationship sometimes being mediated by the emotional competence of students (Espinoza, 2006; Wang and Holcombe, 2010; López-González and Oriol, 2016). In the same way, the experience of violence or abuse in the school setting, as with any form of abuse, leads to a decline in emotional health and, with it, a reduction in school grades for both victims and aggressors (Garaigordobil, 2011; Martínez-Rodríguez, 2017).

In Mathematics, authors such as McLeod (1989, 1992), Gil et al. (2005), and Blanco et al. (2010) have highlighted the importance of emotions in the teaching-learning processes pertaining to the subject. In work conducted in 1992, McLeod proposed that the emotional dimension in the teaching of Mathematics should be addressed by considering three main components: beliefs, attitudes and emotions. Since then, a number of authors have examined the relationship that exists between these components and results in Mathematics in students at different educational stages. The majority of these authors have concluded that significant positive relationships exist between emotions and performance (Mato and de la Torre, 2010; Molera, 2012; Muñoz-Cantero et al., 2018). McLeod's approach to the affective dimension is exclusively designed for the area of mathematics in the sense that the beliefs, attitudes and emotions that make is up describe affective responses to situations related with the subject of Mathematics (McLeod, 1992). Nonetheless, for some time now, examinations of the affective dimension in Mathematics have been conducted alongside analyses of other abilities that are not only related to this subject but, instead, are more holistic in nature and reflect the psychoemotional status of individuals. This has given rise to the concept of the emotionally literate individual in Mathematics. This covers everything involved in the development of an individual's emotional intelligence in the context of Mathematics and the way they manage to find a way to interact with this ambit, whilst also taking into account both one's own feelings and emotions as well as those of others (Gómez-Chacón, 2000). Consequently, research has begun to examine the influence of student's general psychoemotional state on Mathematics achievement. Gallesi and Matalinares Calvet (2012) found a significant and positive correlation between logic-mathematics performance of a group of primary school students and their resilience, understood as a global response that activates protective mechanisms and enables the individual to come away strengthened from a situation that is, at first, perceived to be adverse (Rutter, 1991). Specifically, of the five dimensions considered by this study and used to measure resilience in students, three (self-esteem, empathy and autonomy) were found to be significantly related with performance. Similarly, according to the study by Donolato et al. (2020), resilience was also found to have a significant effect on the mathematics performance of a group of Italian middle school students. In the same line, Ros-Morente et al. (2017) reported that Mathematics performance in a group of students could be predicted, to a large degree, from their emotional develop and self-esteem. In a study conducted with a group of secondary school students, Salcedo-Rodríguez and Pérez-Vázquez (2020) demonstrated that motivation and empathy was weakly, yet significantly, associated with the mathematic ability.

The importance of emotions as an indicator of the global health of students and their impact on academic performance has led educational studies with international reach, such as the aforementioned PISA, to start to gather information on the individual well-being of participants. PISA is an international macro study ran by the Organisation for Economic Co-operation and Development with the aim of identifying the skills held by 15-year-olds in relation to the three areas of mathematics, science and reading comprehension. To this end, participating students performed a series of tests in order to demonstrate their skills and abilities for each of the three ambits mentioned above. In addition, PISA gathers a huge amount of information about the context in which students operate. Such information includes variables pertaining to the family situation, school situation and, in addition, variables that are individual or personal in nature. In the 2015 version of the PISA, data was collected for the first time on the well-being of participating students as a part of the information gathered on their personal state. This made it the first international and educational macro study of its kind (OECD, 2019a). Indeed, in the PISA 2015 questionnaire on students' personal and family background, some questions were included to collect students' perceptions of their well-being. Given the limitations in the scope of the conclusions that could be drawn from these questions, it was decided in the 2018 edition to create a separate questionnaire to collect information on all dimensions of participants' well-being (OECD, 2019a). According to the PISA, student well-being is structured according to three different dimensions. The first is an individual dimension and concerns health status and perceptions about the way in which students feel about themselves and their lives. The second is an academic dimensions and concerns student perceptions about their day-to-day at the institution in which they are undertaking their studies. Finally, the social dimension concerns student perceptions about the relationships they form outside of the educational institution with their parents, their friends, etc. Further, this dimension encapsulates student perceptions about their life in a general sense (OECD, 2019a). The inclusion of this type of information within the data provided by the PISA has led some authors to start to examine relationships between factors that are psychoemotional in nature and studentliteracy. Specifically, Antonelli-Ponti et al. (2021) demonstrated that both the emotional support provided by parents and the sense of belonging at school positively correlated with literacy in the three areas evaluated by PISA 2015 in Brazilian students. In the same study, the sense of belonging at school was also found to have a significant impact on the literacy in these three examined areas. Another variable in the school environment that significantly influences student literacy according to studies based on the analysis of PISA data is the classroom climate (Ruíz de Miguel, 2009; de Jorge-Moreno, 2016). In Spain, the work of Gil-Madrona et al. (2019), based on the analysis of PISA 2015 data, found that while students' anxiety had a negative impact on their science literacy, their sense of belonging to the school and cooperation among students had a positive impact. On the other hand, Rusteholz and Mediavilla (2022) showed bullying to have a negative impact on the literacy in all of the areas evaluated by the PISA in 2018. In real terms, this impact was found to equivalate to the loss of 3–5 months of formal education for victimised students when compared with their non-victimised peers. Nevertheless, very few studies have examined the effect of variables that are psychoemotional in nature on mathematic literacy in Spanish students.

Based on that discussed above, the aim of the present work was to identify the psychoemotional variables that impact the mathematical literacy of Spanish students and quantify their effect by analysing data provided by the PISA in 2018.

2. Materials and methods

The sample used in the present study corresponds to the Spanish sample of the 2018 edition of the PISA. Specifically, the sample is composed of 35,943 students aged 15 years, of which 50.05% are male and the remainder are female.

The dependent variable specified when conducting modelling analysis was student literacy in the subject of Mathematics, which is defined as an individual's capacity to formulate, employ, and interpret mathematics in a variety of contexts (OECD, 2019d). The PISA measured mathematical literacy according to measures known as plausible values. In the PISA, plausible values are representations of the range of potential scores used to evaluate students. The values are drawn randomly from the probability distribution pertaining to each student's marks or grades, the calculation of which considers the responses given by students to the mathematical tests they complete, in addition to some variables pertaining to context (OECD, 2019b). Plausible values are scaled in such a way that, approximately, they produce a mean of 500 and a standard deviation of 100, when drawn from all of the countries that make up the OECD. In 2018, the PISA produced 10 plausible values for Mathematics. Thus, each one of these 10 values will be examined as an independent variable and the outcomes of these analyses will be combined in line with that outlined by the OECD (2009).

As independent variables, the present study considered the indices provided by the PISA that reflect the psychoemotional state of students. These indices are presented in Table 1.

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TABLE 1 Examined independent variables.

Ambit	Variable	Description
Individual	COMPETE	Competitiveness
	FEARFAIL	Fear of failure
	EUDMONIA	Perception of purpose or meaning in life
	POSFEEL	Perception of positive feelings (happiness, joy…)
	RESILIENCE	Resilience
	BODYIMAGE	Satisfaction with appearance and body image
	WORKMAST	Motivation to improve and task mastery through effort
	MASTGOAL	Motivation to achieve goals and maximise learning
School	BELONGSCH	Sense of belonging at the academic institution
	BULLYING	Experiences of bullying suffered by the student
	PERCOOP	Perception of cooperation by students at the academic institution
	PERCOMP	Perception of competitiveness by students at the academic institution
Social	PAREMOSUP	Perceived emotional support received from parents
	SOCONPAR	Feelings of social connection and attachment to parents

The PISA estimates values for these indices for all students as a function of the responses they provide to a series of questions contained in the questionnaire on their personal and family context and in the questionnaire on their well-being. Table 2 shows the items used for the calculation of each of the indices.

Each of the items is answered by students using a Likert scale with four or five response categories, depending on the item. The responses to the items constituting each index are then modelled and subsequently scaled to produce the index itself, which is continuous in nature. The scaling process is carried out in such a way that the mean of each index is equal to 0 when all students from OECD countries are considered. Positive variable ratings suggest more positive responses in relation to the average student from OECD countries, whilst negative ratings suggest more negative responses than these students (OECD, 2019b). At the time of analysing information provided by the PISA, it is necessary to consider the hierarchical nature of the data obtained. This hierarchy responds to the fact that each individual student is enrolled at a particular school or educational institution. As a result, characteristics inherent to the institution can exert a certain degree of influence over student literacy, meaning that the assumption of independence does not apply to the observations made. This means it is not possible to apply traditional techniques of linear regression, given that the fulfilment of this

TABLE 2 Items considered by PISA for the calculation of the independent variables.

Variable	Items
COMPETE	I enjoy working in situations involving competition with others.
	It is important for me to perform better than other people on a task.
	I try harder when I'm in competition with other people.
FEARFAIL	When I am failing, I worry about what others think of me.
	When I am failing, I am afraid that I might not have enough talent.
	When I am failing, this makes me doubt my plans for the future.
EUDMONIA	My life has clear meaning or purpose.
	I have discovered a satisfactory meaning in life.
	I have a clear sense of what gives meaning to my life.
POSFEEL	Thinking about yourself and how you normally feel: how often do you feel joyful?
	Thinking about yourself and how you normally feel: how often do you feel cheerful?
	Thinking about yourself and how you normally feel: how often do you feel happy?
RESILIENCE	I usually manage one way or another.
	I feel proud that I have accomplished things.
	I feel that I can handle many things at a time.
	My belief in myself gets me through hard times.
	When I'm in a difficult situation, I can usually find my way out of it.
BODYIMAGE	I like my look just the way it is.
	I consider myself to be attractive.
	I like my body.
	I like the way my clothes fit me.
WORKMAST	I find satisfaction in working as hard as I can.
	Once I start a task, I persist until it is finished.
	Part of the enjoyment I get from doing things is when I improve on my past performance.
MASTGOAL	My goal is to learn as much as possible.
	My goal is to completely master the material presented in my classes.
	My goal is to understand the content of my classes as thoroughly as possible.
BELONGSCH	I feel like an outsider (or left out of things) at school.
	I make friends easily at school.
	I feel like I belong at school.
	I feel awkward and out of place in my school.
	Other students seem to like me.
	I feel lonely at school.
BULLYING	Other students left me out of things on purpose.
	Other students made fun of me.
	I was threatened by other students.

(Continued)

TABLE 2 (Continued)

Variable	Items
PERCOOP	Students seem to value cooperation.
	It seems that students are cooperating with each other.
	Students seem to share the feeling that cooperating with each other is important.
PERCOMP	Students seem to value competition.
	It seems that students are competing with each other.
	Students seem to share the feeling that competing with each other is important.
PAREMOSUP	My parents support my educational efforts and achievements.
	My parents support me when I am facing difficulties at school.
	My parents encourage me to be confident.
SOCONPAR	My parents help me as much as I need.
	My parents show that they care.
	My parents try to understand my problems and worries.
	My parents encourage me to make my own decisions.

OECD (2019c).

assumption is an essential requisite. Instead, hierarchical regression techniques, also known as multilevel regression (Hox, 2002; Cebolla-Boado, 2013) consider the dependence between observations at the time of modelling outcomes, making them much more appropriate for the analysis of data produced by the PISA. Multilevel regression breaks down the total variability of observations as a function of the nested levels included within the model and indicates the proportion of variance that can be attributed to each level. Data analysis in the present work considered two levels. Firstly, the student level and, secondly, the school level. Modelling normally starts by estimating known parameters and producing a null model, which does not consider any predictor when producing an estimation. Following this, the independent variables from one of the two levels or from both of the levels can be included in the model in order to explain variability in the response variable. In the present study, the independent variables considered described student characteristics, meaning that all independent variables pertained to the student level.

Data were analysed using version 25 of the statistical analysis software SPSS (IBM Corporation, 2017). Estimations were considered to be significant when the absolute value of estimation was 2 times greater than its corresponding standard error term.

3. Results

Firstly, this section will present outcomes of preliminary descriptive analysis conducted of the dependent variable and the independent variables. Next, the estimations produced by the multilevel regression model will be presented.

According to the outcomes presented in Table 3, literacy by Spanish students in the subject of Mathematics ranges between scores of 127.46 and 808.39, pertaining to a range of 680.93. Despite this range, scores pertaining to the middle 50% of students ranged between 432.39 and 553.25. The average score indicating the literacy of participating students in Mathematics was 491.16, placing them slightly below the average literacy of students from the OECD, which pertains to a score around 500. In the same way, the standard deviation pertaining to literacy in Mathematics was 87.54, which is lower than the average standard deviation of around 100 reported for OECD countries.

Next, Figures 1, 2 presents box and whisker plots of data pertaining to the independent variables considered in the regression model.

According to data presented in the figure presented above, Spanish students reported high levels of competitiveness (0.0354), with this level being slightly higher than the average reported for students from OECD countries (with this being 0). When compared with the average OECD student, the majority of students in the present sample had more clear perceptions of the meaning or purpose of their lives (0.0864). A noteworthy amount of variability was presented in relation to the index measuring perceived resilience in students. On the one hand, more than half of participating Spanish students gave negative indices of resilience. This suggests that, on average, the majority of these students considered themselves to be less resilient than OECD students. Indeed, some students reported extremely low levels of resilience when compared with the main bulk of the present sample. However, on the other hand, the average value for this index was positive, given that a group of students was found to report levels of resilience that were much higher than 0.

As shown in Figure 2, the majority of participating students in the present study felt a greater sense of belonging at school than the average student from OECD countries. Further, it was observed that Spanish students were less exposed to bullying at their educational institution than were students, on average, from OECD countries. Despite this, a reasonable number of students presented very high scores in relation to the bullying index.

Next, estimations produced by multilevel modelling analysis are presented, starting with those provided by the null model. These outcomes are presented in Table 4.

The null model reveals that average literacy in Mathematics pertaining to Spanish students corresponds to a score of 489.18. Estimations pertaining to the variability existing both between schools and between students at each school were found to differ significantly from 0, with variability pertaining to the latter being much larger than that pertaining to the former. The deviance value produced for the null model was 419970.28.

For the next step in the modelling process, predictors were added to the model pertaining to the student level presented in Table 1. Estimations for this new model can be consulted in Table 5.

The multilevel model reveals that average literacy of Spanish subjects in the subject of Mathematics corresponded to a score of more than 500 when the value of all indices serving as independent variables was held at 0.

With regards to independent variables under examination pertaining to the individual component of psychoemotional well-being, variables describing resilience (RESILIENCE), motivation to achieve goals as fully as possible (MASTGOAL) and perceiving to have a clear meaning to life (EUDMONIA) had the greatest impact on mathematics literacy in students. The first two of these variables were positively correlated, indicating that, on the one hand, more resilient students and those showing greater interest in achieving greater

TABLE 3 Descriptive statistics for the dependent variable.

	Minimum	Mean	25th perc.	Median	75th perc.	Standard deviation	Maximum
Mathematical literacy	127.46	491.16	432.39	495.45	553.25	87.54	808.39

perc. = percentile.

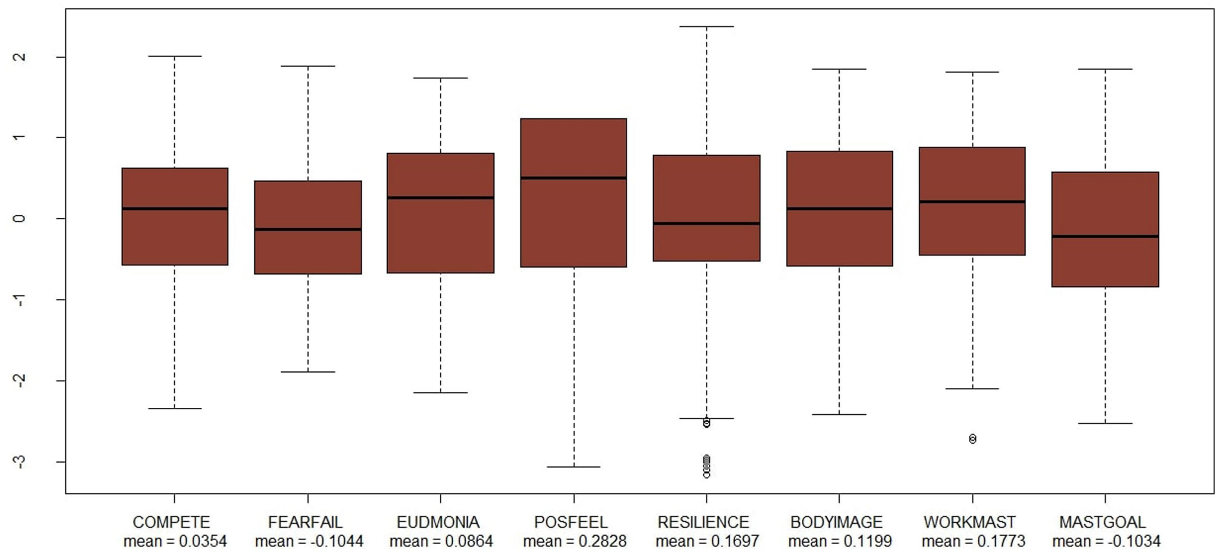

FIGURE 1
Box-and-whisker plots for the personal indices independent variables.

mastery over academic content performed better in Mathematics. In contrast, the coefficient associated with the variable EUDMONIA was negative, with students reporting having a clearer purpose in life also tending to perform more poorly in Mathematics. Specifically, each point increase in indices measuring resilience, motivation to achieve goals and life purpose in students led to an increase of 10.47 and 10, and a decrease of 13.74, respectively, in their literacy on the subject when all other predictors were held stable. On the other hand, student competitiveness (COMPET) was directly related with their Mathematics score, in such a way that each unit increase in the index measuring this characteristic led to an increase of 6.04 in the score achieved by students in the subject of Mathematics. It can also be seen, that as student perceptions of their appearance and body image (BODYIMAGE) improved, their Mathematics score decreased. According to the developed model, neither fear of failing (FEARFAIL) nor the level of motivation to achieve academic improvement (WORKMAST) reported by students was associated with outcomes in Mathematics.

With regards to the indices used to indicate aspects of the psychoemotional state of students as a function of their relationship with their school environment, the index measuring exposure to bullying at school was shown to have the greatest impact when it came to explaining variability in Mathematics literacy. Students reporting having suffered *bullying* (BULLYING) at school were found to have significantly lower Mathematics scores, with scores being 7.93 points lower for each unit increase in the variable measuring exposure to this type of mistreatment. Further, perceptions of competitiveness (PERCOMP) at the educational institution were observed to negatively impact the mathematics outcomes achieved by students, whilst perceptions of cooperation (PERCOOP) had the opposite effect.

In the social ambit, the level of connection and attachment students reported to have with their parents was positively related with their Mathematics scores. This is evidenced by the coefficient associated with the SOCONPAR index, whilst the emotional support students perceived to receive from their parents (PAREMOSUP) did not have a meaningful impact on their Mathematics literacy.

Finally, variance values produced by the multilevel regression model pertaining to differences between educational institutions and variance due to differences between students within the same educational institution were 764.67 and 5884.69, respectively, with the corresponding deviance value being 187919.62. This suggests that, in comparison with the null multilevel regression model, the inclusion of dependent variables measuring student psychoemotional well-being significantly improved model fit and, as a result, its predictive power.

4. Discussion

Existing scientific literature strongly suggests that the psychoemotional state of individuals has an impact on the different ambits of their daily life. In the case of students, the study of the way in which psychoemotional well-being affects their academic life is of particular interest. In this context, the present work focused on

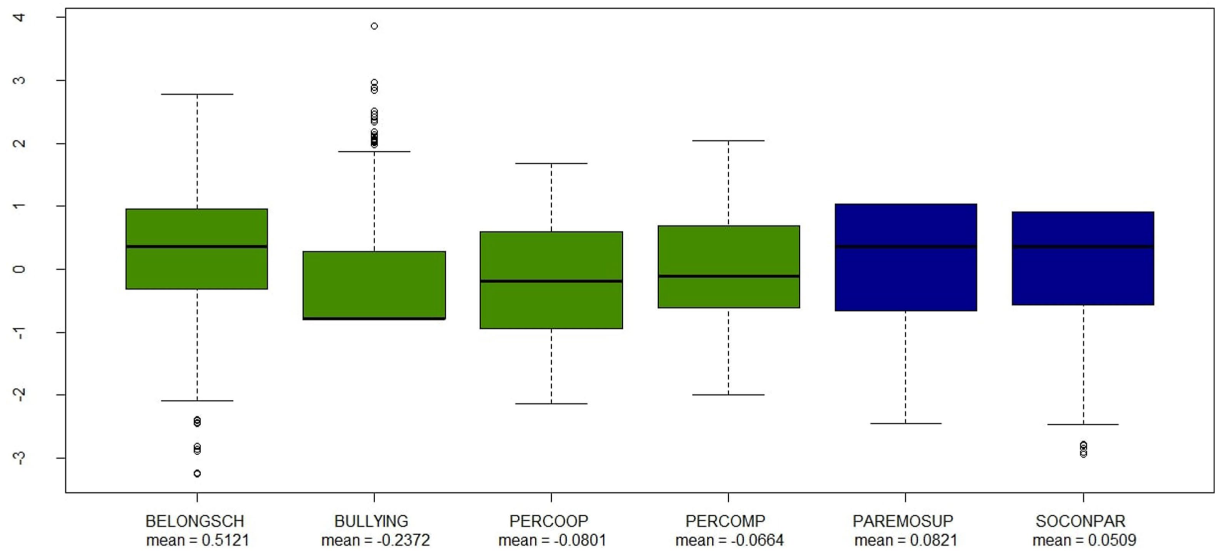

FIGURE 2
Box-and-whisker plots for the school (in green) and social (in blue) indices independent variables.

TABLE 4 Estimates and standard errors of the parameters of the null multilevel regression model.

Variables	Estimate	Standard error
Intercept	489.18	1.41
School level variance	1162.25	101.01
Student level variance	6563.93	115.46

identifying the variables capable of indicating psychoemotional health in Spanish students and the influence of these variables on performance in the subject of Mathematics through an examination of data reported in PISA 2018.

The present work highlights that students' emotions are intimately related with their Mathematics performance. Effectively, emotional state, corresponding to the individual component of psychoemotional well-being in students, the academic or school component and the social component were confirmed to be related with the score or grade obtained in Mathematics. Present findings coincide with those presented by Elizondo-Moreno et al. (2018), in the sense that positive emotions were associated with higher scores in Mathematics and vice versa.

Within the group of predictors of the personal component of psychoemotional well-being examined in the present study, resilience, motivation towards achieving optimal learning and a sense of purpose in life stood out for the size of the coefficient associated with corresponding variables. The positive relationship between resilience and mathematics achievement reported in our paper was also reported by Gallesi and Matalinares Calvet (2012) and Donolato et al. (2020) in Peruvian and Italian students, respectively. As a consequence of this relationship, it would be useful for teachers to promote this trait in classrooms with the aim of achievement better Mathematics outcomes for their students. Although Mathematics teachers may suffer from a lack of training to achieve this outcome, the promotion of resilience in the classroom can start by, for example, supporting students to manage the frustration derived from tackling challenging subject material or motivating students through the appropriate methodologies, resources and activities. Motivating students in this way may also be beneficial if it serves to instill in students the desire to learn, which has been shown to have positive repercussions on Mathematics outcomes. With regards to the direction of the association between student Mathematics scores and the perception of having a clear objective or purpose in life, it is a potentially surprising finding that a negative association emerged when the opposite relationship may have been expected. As stated by Cohen and Cairns (2012), a sense of meaning in life is a hugely important element of individual well-being. Nonetheless, the process of searching to define this goal could become stressful and, therefore, translate into impinged well-being at the level of the individual, with this possibly having implications on the different contexts of their life, including the academic context. Another potential explication of this inverse association is related with the role played by Mathematics regarding student life goals. When Mathematics does not form part of the student's life goals, neither as an outcome nor as a means, it makes sense that the relationship between Mathematics and goals or purpose in life would become counterproductive. However, work such as that of Erdem and Kaya (2021), also based on the analysis of PISA data, supports the results of our study by also reporting a negative effect, albeit of a smaller magnitude, between having a clear purpose in life and the mathematical literacy of Turkish students. In another sense, it also serves to highlight that a negative association was found between students' perceptions of their appearance and Mathematics performance in the present study. Previously conducted scientific literature has barely examined the existing relationship between perception of physical appearance and Mathematics grades. In a broader sense and in consideration of the fact that satisfaction with external appearance is one of the main variables related with personal self-esteem (Broc, 2000), it can be confirmed that present findings contradict the majority of those reported by reviewed work conducted on the topic. Indeed, these studies evidence either a positive

TABLE 5 Estimates and standard errors of the parameters of the multilevel regression model including student-level predictors.

Variables	Estimate	Standard error
Intercept	500.34	1.79
COMPETE	6.04	1.21
FEARFAIL	−1.59	1.51
EUDMONIA	−13.74	1.08
POSFEEL	−2.42	1.13
RESILIENCE	10.47	1.28
BODYIMAGE	−4.88	1.16
WORKMAST	−0.67	1.33
MASTGOAL	10.00	1.20
BELONGSCH	−0.87	1.08
BULLYING	−7.93	1.19
PERCOMP	−3.00	1.19
PERCOOP	5.04	1.23
PAREMOSUP	0.76	1.36
SOCONPAR	5.44	1.53
School level variance	764.67	55.62
Student level variance	5884.69	100.40

association or no association between self-esteem and performance in Mathematics (Bodkin-Andrews et al., 2010; Ros-Morente et al., 2017; Cid-Sillero et al., 2020).

With regards to the variables corresponding to the school and social component of the psychoemotional well-being of students for which significant outcomes were produced in the model predicting Mathematics scores, students' parents played a key role. Such was this the case that a consolidated and positive link between parents and children counteracts, to some extent, the effect that negative experiences, such as those related with bullying at the academic institution, may have on the mathematics performance of students. In this sense, our findings are in line with those reported by Antonelli-Ponti et al. (2021) who pointed out a positive relationship between parental support and students' mathematical literacy and with those highlighted by Rusteholz and Mediavilla (2022) in pointing out that bullying harms mathematical achievement. In addition, school climate, as measured in the present work in accordance with student perceptions of competitiveness and cooperation, was demonstrated to have a meaningful impact on the outcomes obtained by students in Mathematics, as proved by Gil-Madrona et al. (2019) in the area of science.

With regards to limitations of the present work, on the one hand, a number are inherent to the nature of the study design itself of the PISA. For instance, it was not mandatory to respond to questions regarding the psychoemotional state of students, making it impossible to examine the effect of other student traits, such as empathy or adaptability, on their performance in Mathematics. On the other hand, the significance of the variance between students and between schools indicates the existence of other sources of variability that were not controlled for in the present work and that may have an impact on student Mathematics performance. The magnitude of variability due to student differences was far greater than that found to exist between academic institutions and indicates that important variables were not examined that mainly pertain to student characteristics. Effectively, it is possible that, in addition to their psychoemotional well-being, other characteristics of the students' personal and family context may also have a significant influence on the results they obtain in Mathematics. These variables were not included as predictors of the multilevel regression model developed in the present study as they were outside of the scope of the present work. Indeed, authors such as Molina-Muñoz et al. (2022) and Gamazo et al. (2018) have demonstrated that variables such as socioeconomic status and having to retake courses have an influence of the outcomes obtained by students in Mathematics. It is also even possible that the individual, social and family context to which students belong dictates the impact that variables of a psychoemotional nature have on Mathematics performance.

In conclusion, it is important to highlight the importance of psychological and emotional well-being in students and the need to support their emotional intelligence, alongside traditional cognitive intelligence, as both are likely to have a similarly meaningful impact on the academic outcomes achieved by students.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.oecd.org/pisa/data/.

Author contributions

DM-M, JC-G, and EM-P contributed to conception and design of the study. DM-M and JC-G organized the database. DM-M and EM-P performed the statistical analysis. DM-M wrote the first draft of the manuscript. JC-G and EM-P wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Attitudes toward mathematics/statistics, anxiety, self-efficacy and academic performance: an artificial neural network

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Mathematics and statistical skills are crucial to daily life. However, many students found mathematics difficult to learn and understand. This research aimed to find relationships between mathematics and statistical attitudes and emotional dimensions, such as anxiety or self-efficacy. The sample consisted of two groups: the first group was formed by 276 Spanish students (75.7% female with an average age of 19.92 years) from different degrees at the University of Granada and the second one by agroup of 19 secondary school students from of a Secondary School in Granada, Spain (57.9% male students between 14 and 16 years of age from a public school). The instruments applied were a scale of attitude toward mathematics, a scale of attitude toward statistics, a scale to assess mathematical anxiety, and a scale to assess self-efficacy. An artificial neural network for the backpropagation algorithm was designed using dependent variable. The results showed a negative impact of anxiety on those attitudes, while self-efficacy had a positive impact on those mentioned attitudes. Therefore, emotional education is important in the well-being, and teaching in mathematics. The usefulness of the innovative neural network analysis in predicting the constructs evaluated in this study can be highlighted.

KEYWORDS

attitudes, anxiety, educational psychology, mathematics, artificial neural network, university student

1. Introduction

When we talk about attitudes toward mathematics we are somehow referring to the affective component of the construct (Geisler et al., 2023) that Emmioğlu and Çapa-Aydın (2012, p. 95) define as a "multidimensional construct that stands for students' learned predispositions to respond positively or negatively with regard to statistics." It is necessary not to neglect this non-cognitive component so relevant to the teaching/learning process in Mathematics and Statistics (García-Suárez et al., 2023; Spencer et al., 2023). The affective dimension of competencies such as emotional competence is part of the curriculum to be addressed in the teaching/learning processes of mathematics. Therefore, the evaluation of these attitudes is essential for academic achievement and performance improvement, since the affection or rejection toward mathematics has an impact on the interest and motivation toward mathematics, as indicated by Feregrino et al. (2021). Also within an affective-emotional dimension, the term self-efficacy refers to "beliefs about their ability to perform statistical/mathematical tasks (Spencer, 2023, p. 1), and the term mathematical anxiety refers to "feelings of tension and discomfort that might prevent someone from carrying out his or her actual capability in mathematical problems" (Ashcraft, cited in Özcan and Eren Gümüş, 2019, p. 119) and this may be related to a higher frequency of negative attitudes toward mathematics (García-Suárez et al., 2023) with the consequences this may have for their learning and performance and for the specific process for the instruction and learning of mathematics and statistics. By assessing these constructs we focus on non-cognitive aspects, which have sometimes been given less importance, and may be relevant to achieve meaningful learning in mathematics and improve its teaching (Ávila-Toscano et al., 2020; Sánchez et al., 2022; García-Suárez et al., 2023).

Regarding gender, Galende et al. (2020) reported more positive attitudes toward mathematics in males compared to females. Paechter et al. (2017) found higher levels of math anxiety in females compared to males. Likewise, Ryan et al. (2022) found statistically significant gender differences in the variables of math anxiety, math self-efficacy and perseverance; specifically, it was males who presented higher levels of mathematical self-efficacy and self-concept compared to females, while females presented higher levels of mathematical anxiety compared to males. It should be noted that this has psychoeducational implications for the teaching/learning process since, as indicated by Ryan et al. (2022), women are more concerned about possible difficulties in learning mathematics and lower mathematics achievement than men. In the same line, Rončević Zubković et al. (2021) evaluated mathematical anxiety, mathematical self-concept and learning strategies and mathematical performance in a sample formed by 2,749 Croatian student body, 56% being girls, with a mean age of 14.58 years finding a less positive mathematical self-concept in girls compared to boys and a higher use of so-called learning strategies; girls were also found to have higher levels of mathematics anxiety compared to boys. It was also found that the older the age of the transition to school, the greater the lack of motivation, the positive evaluation of mathematics and the lower the academic performance.

Studies that have previously analyzed the relationship between the constructs included in the present study are shown below. Regarding the relationships between attitudes toward mathematics and the constructs of anxiety and other emotional factors, a recent study (Xiao and Sun, 2021) examined affective-motivational factors such as attitudes and interest toward mathematics, mathematical self-concept and mathematical anxiety in a sample of U.S. students, 51% of whom were male. They found different motivational and affective profiles, being the students with a higher level of motivation and lower level of mathematical anxiety those with higher persistence and mathematical performance. In this study, the importance of this type of results is raised so that teachers can also attend to motivational diversity with individualized instruction. In the same vein, Geisler et al. (2023) indicate that there is some evidence of relationships between the individual interest factor of the construct of attitudes toward mathematics with academic performance, but that more research is needed as the results are not entirely conclusive as there are studies (e.g., Rach and Heinze, 2017) even contradictory that find no relationships between the interest factor and academic performance. Among previously studied theoretical models, those proposed by Paechter et al. (2017), in which other variables such as procrastination are included, stand out. The following instruments were used in this study: the German adaptations of the Statistics Anxiety Rating Scale (STARS; Cruise et al., 1985; Papousek et al., 2012), Revised Mathematics Anxiety Ratings Scale (R-MARS; Baloğlu and Zelhart, 2007), State–Trait-Anxiety Inventory (STAI, German version; Laux et al., 1981) and Procrastination Assessment Scale-Students (PASS; O'Callaghan et al., 2009; Macher et al., 2012). The researchers reached the following conclusions: female students presented higher levels of math anxiety; those with a higher propensity to experience anxiety in general, also experienced higher levels of math anxiety; better grades in mathematics implied lower levels of math anxiety; better grades in mathematics implied surprisingly higher levels of statistical anxiety; math anxiety was directly related to statistical anxiety; males were more prone to procrastination; low grades were related to higher levels of procrastination; and statistical anxiety was related to procrastination, among others. Another model to be highlighted is that proposed by Weidinger et al. (2017), who suggested time interval models were related to motivation and grades. In this study, whose sample consisted of 542 German elementary school students, the instruments were applied over 2 years (from Grades 2 to 4), and the following conclusions were obtained: contrary to what might be expected, the findings in this field showed that negative feedback does not always lead to a decrease in internal or intrinsic motivation. This calls into question the widely held view that the idea of thinking of less proficient, as reflected in poor grades, weakens students' intrinsic motivation. Regarding mathematics anxiety, it is worth mentioning that Orbach et al. (2019) investigated mathematics anxiety by comparing the trait components of mathematics anxiety with real-time assessments of situational anxiety responses among children. In that study, different aspects were measured, such as components of math anxiety, self-assessment of math skills, attitudes toward mathematics, learning motivation, mathematics performance, social anxiety, and intelligence of 1.179 4th and 5th grade students. A negative correlation was observed between a component of mathematics anxiety and academic performance. Lim and Chapman (2015) studied the effects of using mathematics history in mathematics instruction on levels of mathematics anxiety, attitudes, and motivation in grade 11. Four classes from a school in Singapore participated in this experiment. The experimental group of 51 students and control group of 52 students comprised two classes each. The results indicated that the use of stories as a tool for teaching mathematics had desirable outcomes. Noteworthy are the studies conducted by Abín et al. (2020) and Suren and Kandemir (2020) on their effects on performance. Suren and Kandemir (2020) administered the following instruments to a sample of 777 grade 8 students from a province in the Aegea region of Turkey: Mathematical Motivation Scale (MMS) and Mathematics Anxiety Scale for Elementary School Students (MASESS). According to that research, the levels of anxiety and motivation may have a positive relationship when it comes down Mathematics. In fact, anxiety was found to predict performance at a higher level, followed by motivation. The same year, in a study by Abín et al. (2020), a large sample of 2.365 Spanish students from four secondary school grades (12–16 years) participated. In that research, information was collected on students' intellectual abilities, perceived competence in mathematics, perceived usefulness of mathematics,

mathematics anxiety, causal attributions, and mathematics achievement. They found differences based on sex, but no significant effects of affective or motivational variables. Özcan and Eren Gümüş (2019) investigated the direct and indirect effects of several noncognitive constructs, such as mathematical self-efficacy, mathematical anxiety, and metacognitive expertise, on mathematical problem solving in high school students. The participants were 517 Turkish grade 7 students. They found an effect of mathematical anxiety and academic motivation, with self-efficacy as a mediating variable in solving mathematical problems. Likewise, the effects of metacognitive experience mediated the variables of mathematical anxiety, self-efficacy, and motivation. These metacognitive experiences also influenced the resolution of mathematical problems. Also, Li et al. (2021) conducted a meta-analysis to determine the relationship between mathematics anxiety and students' motivation to learn mathematics and found a moderate negative correlation between students' mathematics motivation and mathematics anxiety. Regarding the relationships between attitudes toward mathematics and the variable self-efficacy, there is also previous research (Czocher et al., 2020) that found that academic self-efficacy was one of the relevant predictor variables of motivation and persistence in STEAM (science, technology, engineering, art, and mathematics) careers. Czocher et al. (2020) proposed the training of self-efficacy and competence through mathematical modeling in university students, indicating the importance of an intervention to improve the construction of such self-efficacy. Along the same lines, another recent study highlights the importance of mathematics attitudes such as academic interest and self-concept and aspects such as degree of satisfaction and perceived achievement given their influence on the dropout rate during the first university years (Geisler et al., 2023). Czocher et al. (2020) found in first-year undergraduate students at a German university in some mathematics major (mathematics program and teacher education program) aged 17–33 years, using a gender-balanced sample, that attitudes toward mathematics such as mathematical interest and mathematical self-concept correlated inversely with the risk of academic dropout; to be specific, satisfaction was a mediating variable for both academic interest and academic self-concept. Another study assessed attitudes toward statistics, statistical self-efficacy, task value and task effort using a convenience sample of 189 students, mostly second year engineering students, more than half white, 76.2% male (Spencer et al., 2023). They also found that self-efficacy and affect were predictive variables of overall course grade, although not of course retention.

Focusing on all the indicated constructs, another previous research analyzed attitudes toward mathematics and other aspects related to the emotional dimension such as perceived self-efficacy and math anxiety in a sample of 304 Irish Secondary Education students, 60.2% male (Ryan et al., 2022). These authors considered it essential to start assessing motivation toward mathematics in this period, especially in view of the implementation of a new curriculum in this area in that country. They found in the students participating in this study positive self-confidence and also high levels of commitment and motivation in mathematics even after 1 year of instruction. Özcan and Eren Gümüş (2019) using structural equation modeling found in a study involving Turkish secondary school students, effects of math anxiety and motivation on perceived self-efficacy and metacognitive experience which at the same time impact on the variable academic achievement. Another work also highlighted the importance of interventions aimed at improving self-efficacy and self-regulated learning that has at the same time effects on the non-cognitive factor, that is, on the emotional dimension (enjoyment, achievement, and mathematical anxiety) of the student body, although they found no statistically significant differences in the variable academic performance in mathematics after such intervention (Gamlem et al., 2019). Likewise, another study conducted in 2022 by Rovan et al. (2022) examined the extent to which prior motivational beliefs, such as self-efficacy and subjective value, in a sample consisting of 237 future first-year elementary school teachers are related to their prior experiences related to mathematical learning and math anxiety. They found that prior experience was a predictor variable of mathematics self-efficacy and subjective value. The variable of prior motivational beliefs was also a predictor variable of mathematics anxiety and somewhat in the participation in the teaching/learning process in the prospective teachers in the previous study.

More recently, García-Suárez et al. (2023) also analyzed the affective-emotional dimension, specifically mathematical anxiety and the level of self-confidence, in a sample of 174 first-year, undergraduate engineering students from one of the centers of the University Network of the University of Guadalajara (Mexico). They found, in general terms, a tendency toward a moderate level of math anxiety, but they also found very high levels of anxiety in some students. They also found statistically significant negative correlations between the levels of math anxiety and the degree of self-confidence; The authors show that even in mathematics-related careers, these students may present levels of anxiety that are important to evaluate with a view to improving the teaching/learning process.

Regarding recent studies carried out in Spain, a study evaluated attitudes toward mathematics in a sample of 81 university students belonging to the Primary Education degree, finding (Garcia-Manrubia et al., 2022): (a) values considered adequate for the motivation and confidence factors; (b) values considered medium for the low interest factor; and (c) medium-low values for the liking and anxiety factors. Likewise, this study highlighted the need, with a view to the training of future teachers, to further deepen the scoring of these constructs in future research, especially considering the socio-affective domain. Also using a sample of Spanish students, it is worth mentioning the study by Hossein-Mohand and Hossein-Mohand (2023), which aimed to analyze the effect of motivation on the perception of mathematics in high school students. The instrument consisted of 135 items with six dimensions and 31 indicators, following the procedure of Rosenbluth et al. (2016). This instrument was applied to 2039 students from various educational levels in the centers of the Autonomous City of Melilla. In this study, no correlations were found between sex, educational level, and motivation. The researchers reached the following conclusions: motivation levels could be influencing other study behaviors; there were no significant differences between sex and educational level, study time or motivation; there were no differences between motivation and mathematical learning; and there were certain differences between women and men in the teaching variable.

Several instruments have been applied for the evaluation of the above variables, which are as follows: Scale of attitude toward mathematics (Auzmendi, 1992), Scale of attitude toward statistics (Auzmendi, 1992; Darias Morales, 2000), Scale for Assessing Math Anxiety in Secondary education (SAMAS) (Yáñez-Marquina and Villardón-Gallego, 2017) and General Self-Efficacy Scale (EAG) (Baessler and Schwarzer, 1996; Espada et al., 2012). Other instruments to consider are, for example, the Math anxiety subscale of the Fennema-Sherman Mathematics Attitude Scale (MAS; Fennema and Sherman, 1976), which was considered for application, although it was finally discarded because of the greater suitability of the previous instrument for math anxiety, as it has already been applied and adapted to the context of Spanish education and society, showing excellent results. The scale of attitude toward mathematics (Auzmendi, 1992) and scale of attitude toward statistics (Auzmendi, 1992) are brief self-reports in a 25-item format used to assess the relevant dimensions of attitudes toward mathematics and statistics. Moreover, these instruments have been applied in the Spanish context, both in primary and secondary education and at post-compulsory levels, which is an indicator of the suitability and effectiveness of both tools. Other instruments selected, such as the mathematical anxiety and self-perceived efficacy instruments, were reduced versions that have been widely administered in the Spanish context and cover the most relevant dimensions of these constructs. Specifically, in the case of mathematics, it is especially relevant to understand the existing attitudes and social and emotional competencies of students in this area. Another noteworthy study is that of Ren et al. (2016), which used the previously adapted Fennema-Sherman scale of mathematical attitudes for primary school teachers. This study was divided into three phases: the first pilot phase to check whether the modifications made were adequate; the second phase with 225 teachers as a sample for a subsequent factor analysis; and the third phase for an invariance analysis with 171 teachers as a sample. The overall results suggested that the revised scale could be used by researchers and program evaluators to reliably measure attitudes toward mathematics among elementary school teachers and could be a valuable tool for assessing the effectiveness of professional development. Regarding the variables of attitudes toward statistics and mathematics, Flores and Auzmendi (2015) verified the suitability of the variables described above for attitudes toward mathematics. In Darias Morales's (2000) study, the same was done for the variables with respect to attitudes toward statistics. Regarding mathematical anxiety, the model used, with duly justified variables, appeared in the study of Yáñez-Marquina and Villardón-Gallego (2017), in which the influences of other scales on its elaboration were also discussed. The Generalized Self-Efficacy Scale (GSES) has been considered (Baessler and Schwarzer, 1996; Espada et al., 2012), and validated by Espada et al. in Spain.

It is worth pointing out the need to continue to study in depth the affective domain related to the mathematics curriculum, considering also that there are still no studies in which the relationships between these constructs are studied by means of the design of artificial neural networks. Precisely, there are already studies that have been demonstrating the usefulness of this type of analysis given the numerous applications that can be derived to see how these variables influence the teaching/learning process (Hwang et al., 2020; Martínez-Ramón et al., 2021) and which would also be appropriate, in this case, in Mathematics due to their potential predictive value for the so-called Mathematics Learning Difficulties (MALD) in students and with the help of the "intelligent tutor" from the teaching environment (Hwang et al., 2020).

Having said that, the present project seeks to study different variables related to students' attitudes toward mathematics and/or statistics, and find relationships between these and other variables, such as academic performance or anxiety generated in different situations involving mathematics and/or statistics. The variables to be addressed are (a) attitudes toward mathematics (disaggregated into anxiety -levels of alteration or nervousness-, agreeableness -levels of affinity with mathematical activity-, usefulness -level of perceived usefulness of mathematics-, motivation -level of motivation generated by mathematics-, and confidence -level of hope generated by mathematics-); (b) attitudes toward statistics (disaggregated into security -related to aspects of anxiety, but also with the perception of security/insecurity with respect to the ability to execute statistical problems-, importance -with certain connotations of satisfaction and valuation of the subject-, usefulness -measures the productivity or benefits that statistics can offer-, and desire to know -including aspects of motivation toward knowledge, although also related to aspects of usefulness-); (c) mathematics anxiety (disaggregated into anxiety in everyday mathematics -anxiety generated by everyday activities involving basic mathematics-, mathematical learning -anxiety generated by the activities performed throughout the learning process in mathematics-, and mathematics tests -anxiety generated by facing and taking mathematics tests-); (c) self-perceived efficiency (self-perceived degree of performance in dealing with various situations); and (d) sociodemographic data (sex, age, grade, degree, and average grade).

The overall objective of the present study was to analyze the possible causes of student demotivation toward mathematics, find relationships between these causes and academic performance, and propose a learning situation/teaching unit based on statistics/probability as a response to these possible relationships and/or causes. The specific objectives were as follows: (1) to study the differences in these variables between different groups according to age and sex; (2) to examine the relationship between mathematics and statistics attitudes and study variables; (3) to study differences in mathematical anxiety before and after a mathematics exam; and (4) to design an artificial neural network (ANN) capable of predicting academic performance on the basis of scores on the variables math anxiety, self-efficacy and sociodemographic variables of the study.

The hypotheses of the present work were: (h1) we expected to find statistically significant gender differences in the levels of mathematical anxiety and self-efficacy; (h2) we expected to find associations between attitudes toward mathematics and statistics and the variables of mathematics anxiety and perceived self-efficacy -in particular we expected to find a direct negative relationship between academic performance and variables related to mathematics anxiety, in contrast, a positive direct relationship was expected between academic achievement and variables related to attitudes toward mathematics, statistics, and self-efficacy-; (h3) to study the levels of math anxiety before and after a math test, higher levels of anxiety were expected before taking the exam; (h4) it was expected that the levels of math anxiety, self-efficacy and the sociodemographic variables of the study may contributed to the predictive capacity of the artificial neural network of the variable academic performance in mathematics.

2. Methods

2.1. Design

The ethical principles of the Declaration of Helsinki were considered and an *ex post facto* cross-sectional design was used. After obtaining approval from the Ethics Committee and reporting on the project, self-reported questionnaires with Likert-type responses were administered to participants.

2.2. Participants

The study protocol was approved by the Ethics Committee of the University of Granada (Granada, Spain; 3,376/CEIH/2023). Full-time students between the ages of 12 and 58 years were included. Based on the way of selection of individuals, the sample could be catalogued as a convenience sample. Since there was no missing data, technics meant for this purpose were no needed. The sample comprised 276 Spanish students from different degrees and levels, including 209 females (75.7%) and 67 males (24.3%). The average age of female participants was 19.92 years, whereas that of male participants was 20.07. The female participants were aged between 18 and 59 years, whereas the male participants were between 18 and 45 years. For the study of mathematical anxiety before and after a mathematics exam, the sample comprised 19 secondary education students, consisting of eight females (42.1%) and 11 males (57.9%). The average age of female participants was 14 years, whereas that of male participants was 14.73 years. The female participants were all 14 years old, whereas the male participants were between 14 and 16 years old.

2.3. Procedure

The instruments were collectively administered in classrooms using an online link. The collaborating faculty reported the purpose of the research and its confidentiality in the presence of the members of the research team. Doubts have also been raised in this regard. The secondary school students were contacted by one of the teachers. Thereafter, the project was explained, and data and instruments were administered in the classroom. The teachers were able to clarify any doubts at all times. Data were collected between March and April 2023. The study was voluntary, confidential, and anonymous.

2.4. Measures

Scale of attitude toward mathematics (Auzmendi, 1992) assesses the dimensions of mathematics. This scale evaluates five different aspects, namely anxiety, pleasantness, utility, motivation, and confidence, using 25 different items. These items are evaluated on a continuous response scale ranging from 1 (strongly disagree) to 5 (strongly agree). The reliability analyses showed acceptable internal consistency ($\alpha = 0.914$).

Scale of attitude toward statistics (Auzmendi, 1992) assesses the dimensions of statistics. This scale evaluates four different aspects: security, importance, utility, and desire to know through 25 different items. These items are evaluated on a continuous response scale ranging from 1 (strongly disagree) to 5 (strongly agree). The reliability analyses showed acceptable internal consistency ($\alpha = 0.9$).

Scale for assessing math anxiety in secondary education (SAMAS) (Yáñez-Marquina and Villardón-Gallego, 2017). This self-report scale consists of 20 items with a Likert-type response format ranging from 0 (strongly disagree) to 10 (strongly agree). It comprises the following subscales: (a) *Anxiety regarding everyday mathematics*; (b) *Mathematical learning-anxiety*; and (c) *Math test anxiety*. Internal consistency for the subscale *Anxiety regarding everyday mathematics* was $\alpha = 0.84$; internal consistency for the subscale *Mathematical learning-anxiety* was $\alpha = 0.86$, and internal consistency for the subscale *Math test anxiety* was $\alpha = 0.84$. Examples of items for each of the factors, respectively, would be the following: (a) "I get nervous when calculating the total price of what I bought"; (b) "I get nervous whenever it is math's turn"; (c) "I get more nervous during the math tests than during the exams of other subjects."

General self-efficacy scale (EAG) (Baessler and Schwarzer, 1996; Espada et al., 2012). This instrument consists of 10 items with a 10-step Likert-type response format from 1 = "totally disagree" to 10 = "totally agree." A total score is obtained in which the higher the score, the higher the level of self-efficacy. The internal consistency of the scale is 0.092. An example item is: "I can solve difficult problems if I try hard enough."

Sociodemographic questionnaire on degree, course, sex, age, and average grade. *Ad hoc* preparation.

2.5. Statistical analysis

SPSS Windows software version 26 was used for statistical analysis. Descriptive analyses of this study are also presented (percentages, frequencies, means, and standard deviations). A *t*-test was used to compare means according to sex after verifying that the assumptions of homoscedasticity and normality were met. Stepwise regression analyses were performed. For non-parametric contrasts, the Kolmogorov–Smirnov (for comparing the distribution of two variables), Wilcoxon (for comparing the median value of two variables if they follow different not normal laws), Sign, and Mann–Whitney tests were applied when needed. The regression model included the dimensions of mathematics and statistics attitudes as dependent variables, and the dimensions of anxiety and perceived self-efficacy as independent variables (value of p lower than 0.05).

An artificial neural network for the backpropagation algorithm was designed using academic performance as the dependent variable. All ratings were transformed to a scale ranging from 0 to 10, and the 25th, 50th, and 75th percentiles were calculated to determine the Q1, Q2, Q3, and Q4 quartiles. Knowing the 75th percentile (Q1) in terms of performance, performance was recalculated in another variable so that two groups were dichotomized: a group of students with excellent performance (Q1) with a grade equal to or greater than 8.49 and the performance of the students who were at that level (Q2, Q3, and Q4). For the RNA signal, a fixed seed was established to manage randomness (314159265). Regarding the distribution of the cases, 68% ($n = 187$) were used for the training phase, 20.7% ($n = 57$) for the testing phase, and 11.3% ($n = 31$) for the training, testing, and backup phases, respectively. Regarding network information, the ANN consisted of a factor that was a sex-dichotomous qualitative variable and five-scale covariates (age, self-efficacy, Act_mat, Act_state, and math_anxiety) together with the bias node. The generated hidden layer was composed of two nodes and a bias. Finally, the VD was composed of two nodes (1 = performance of excellence, Q1, and 0 = academic performance, Q2, Q3, and Q4). No scaling was required for input-layer covariates. The activation function of the hidden layer in this research was a hyperbolic tangent. The output layer activation function was a softmax function and the output layer error function was cross-entropy.

TABLE 1 Descriptive summary and internal consistency for mathematics and statistics attitudes, mathematical anxiety, and self-efficacy.

Variables	Minimum	Maximum	Mean	Standard deviation	Cronbach's alpha
Attitudes toward mathematics					
Anxiety	9	45	27.190	8.257	0.746
Pleasure	4	20	9.450	3.907	0.717
Utility	6	30	15.890	4.690	0.717
Motivation	3	15	10.300	2.290	0.716
Trust	3	15	11.180	2.359	0.716
Attitudes toward statistics					
Security	11	55	32.890	8.768	0.730
Importance	6	30	14.860	4.720	0.709
Utility	5	24	14.660	3.460	0.712
Desire to know	5	24	16.500	3.341	0.714
Mathematical anxiety					
Anxiety regarding everyday mathematics	0	70	19.510	16.432	0.700
Mathematical learning-anxiety	0	80	32.420	21.290	0.743
Math test anxiety	0	50	29.650	13.826	0.703
Self-efficacy	12	40	29.590	4.845	0.718

3. Results

3.1. Descriptive results for the whole sample

The descriptive information for the variables mentioned above is shown in Table 1.

3.2. Differences between sexes in levels of the variables mentioned above

Figures 1–4 below show the differences between sexes in the levels of the variables in this study.

3.3. Relationship between mathematics and statistics attitudes and anxiety levels and self-efficacy

The results of the multiple regression models for the dependent variables (mathematics and statistics attitudes) are shown in Tables 2, 3 for the male sample and in Tables 4, 5 for the female sample.

In summary, for the mathematics attitude dimension of anxiety, 53.4–57.4% of the total variance was predicted; for the liking dimension, 19.3–26.3% of the total variance was predicted; for the utility dimension, 15.4–26.6% was predicted; for the motivation dimension, 11.8–14.9% of the total variance was predicted; and for the confidence dimension, 8.5–20.1% of the total variance was predicted.

For the statistical attitude dimension of security, 17.7–31.6% of the total variance was predicted; for the importance dimension, 8.2–11.1% of the total variance was predicted; for the utility dimension, 5.1–6.3% of the total variance was predicted; and for the will to know dimension, 8.4–10.7% of the total variance was predicted.

3.4. Differences in mathematical anxiety before and after a mathematics exam

First, we wanted to test whether the difference between pre- and post-exam mathematical anxiety levels was significant. For this purpose, the Wilcoxon test was applied, showing that, with a significance of 0.028, the difference was sufficient to be considered significant. The difference tended to be positive, showing that post-exam anxiety was lower than pre-exam anxiety.

3.5. Academic performance: proposal of an artificial neural network based on self-efficacy, mathematics and statistics attitudes, mathematical anxiety and sociodemographic variables

Figure 5 shows the graphical representation of the artificial neural network. Scores below 0 indicate a darker link, whereas scores above 0 indicate a lighter line. In addition, the thickness of the line represents the synaptic weight, the value of which are shown in Table 6, the "Parameter Estimates."

In the training phase, the cross-entropy error was 110.057 with 27.8% of incorrect forecasts using one consecutive step without error reduction as the stopping rule. In the testing phase, the cross-entropy error was 27.818, and the incorrect forecasts were reduced to 19.3%. Finally, during the reserve phase, the incorrect forecasts were 12.9%. The dependent variable was "grade" (academic excellence), and it was specified that the error calculations were based on a verification sample. Table 6, "Parameter estimates," shows the synaptic weights in the interactions between the nodes of the different layers.

Table 7, "Classification," shows how in the training phase, the algorithm was able to predict 72.2% of the cases. Subsequently, when

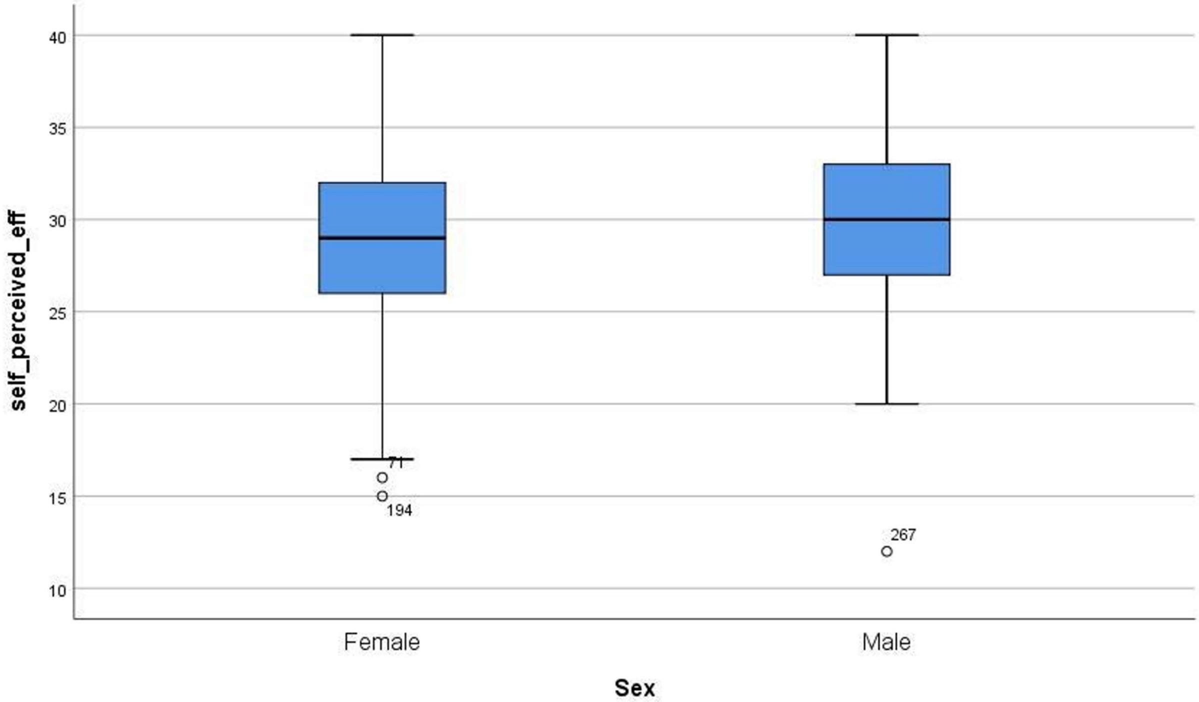

FIGURE 1
Differences between sexes in levels of self-efficiency.

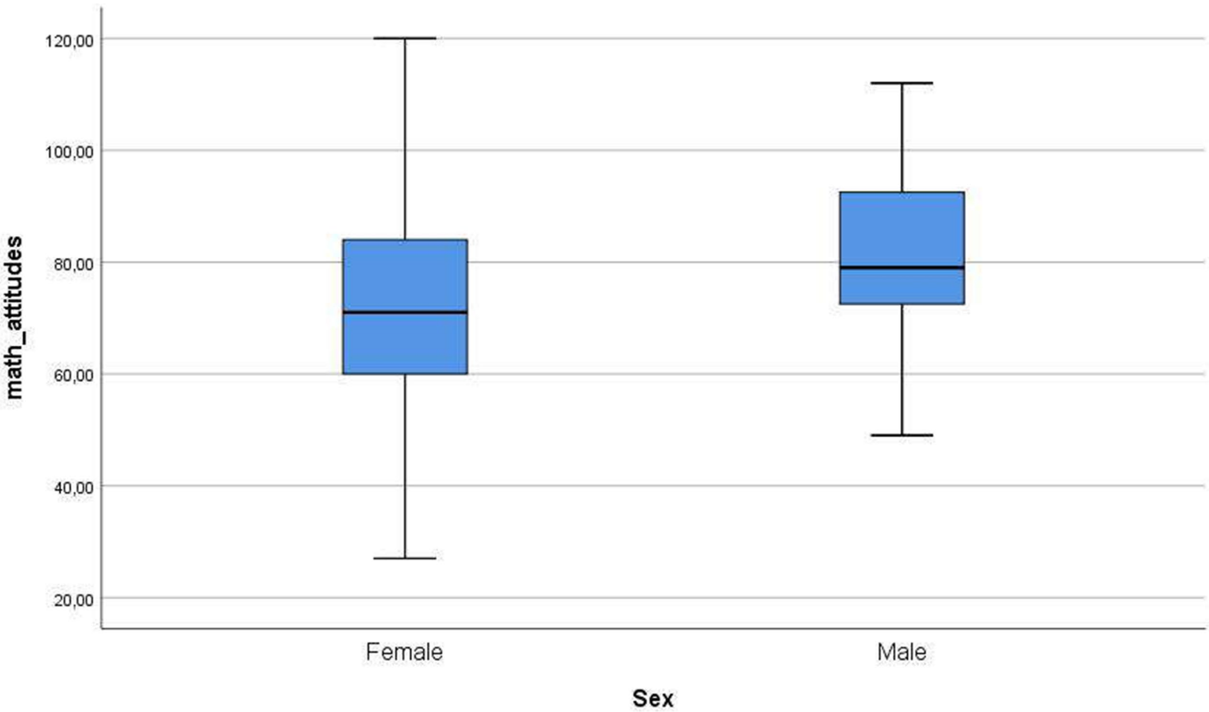

FIGURE 2
Differences between sexes in levels of mathematics attitudes.

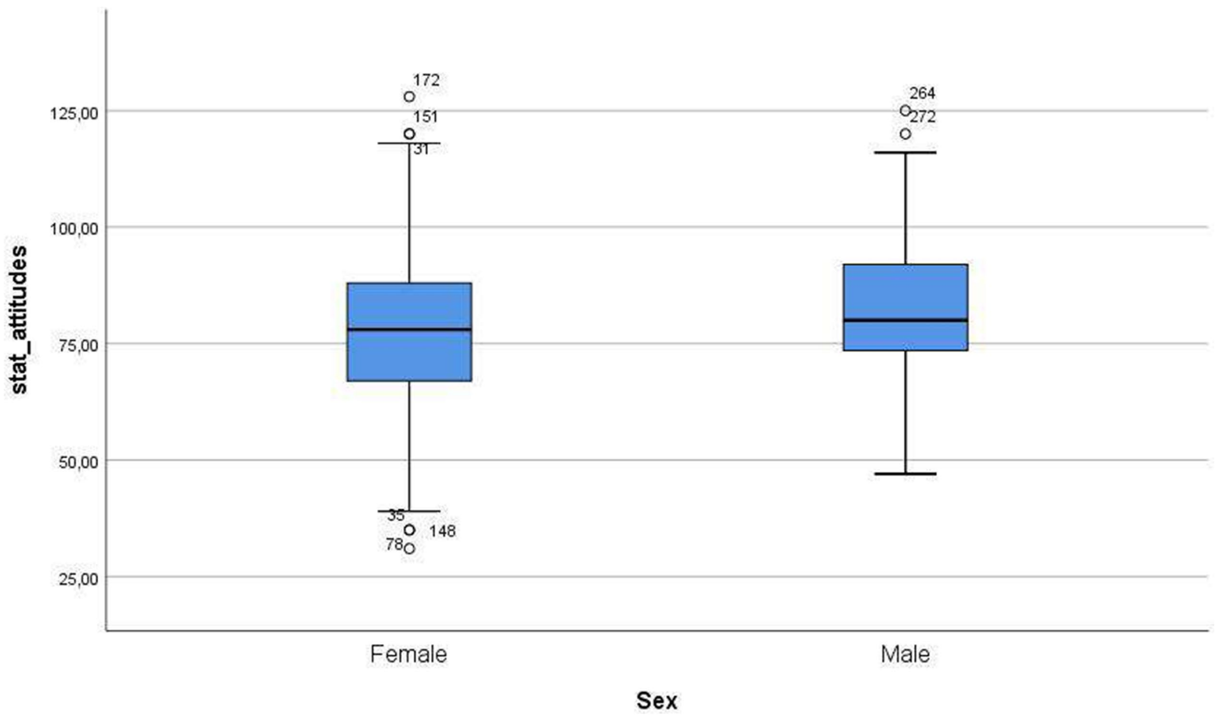

FIGURE 3
Differences between sexes in levels of statistics attitudes.

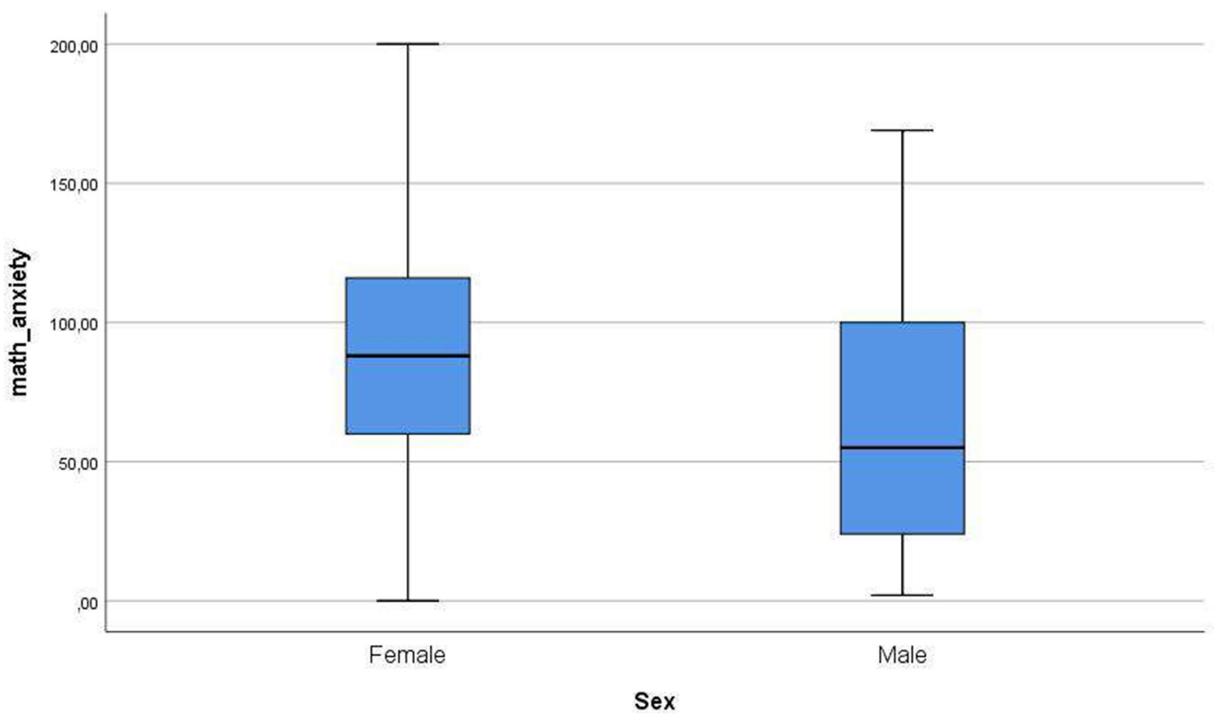

FIGURE 4
Differences between sexes in levels of mathematical anxiety.

putting the algorithm to the test again and perfecting it, it reached a value of 80%, which was even higher when facing the cases reserved to start the ANN, facing cases that it had not previously analyzed, and reaching a predictive capacity of 87.1%.

The area under the curve is above the diagonal; therefore, the results obtained are not due to chance. In the COR graphs of sensitivity, gain, and elevation, the behavior of the VI was observed; more specifically, VI = 0 and VI = 1 (Figures 6–8 and Table 8).

TABLE 2 Multiple linear regression models for the dimensions of the mathematics attitudes (dependent variable) in male.

Independent variables	*B*	CI (95%)		β	SE	*p*
		Lower bound	Upper bound			
Anxiety (R^2=0.534)						
Math anxiety in exams	−0.204	−0.340	−0.067	−0.410	0.068	0.004
Anxiety in mathematical learning	−0.129	−0.225	−0.033	−0.367	0.048	0.009
Pleasure (R^2=0.193)						
Anxiety in mathematical learning	−0.084	−0.127	−0.042	−0.440	0.021	<0.001
Utility (R^2=0.266)						
Anxiety in mathematical learning	−0.122	−0.144	−0.060	−0.516	0.021	<0.001
Motivation (R^2=0.118)						
Math anxiety in exams	−0.063	−0.105	−0.200	−0.344	0.021	0.004
Confidence (R^2=0.085)						
Everyday mathematical anxiety	−0.040	−0.072	−0.008	−0.292	0.016	0.016

R^2, regression coefficient of determination; B, regression coefficient; CI, confidence interval; β, adjusted coefficient from multiple linear regression analysis; SE, coefficient standard error.

TABLE 3 Multiple linear regression models for the dimensions of the statistics attitudes (dependent variable) in male.

Independent variables	*B*	CI (95%)		β	SE	*p*
		Lower bound	Upper bound			
Safety (R^2=0.177)						
Anxiety in mathematical learning	−0.174	−0.267	−0.081	−0.420	0.047	<0.001
Importance (R^2=0.082)						
Math anxiety in exams	−0.096	−0.176	−0.016	−0.286	0.040	0.019
Utility (R^2=0.051)						
Everyday mathematical anxiety	0.028	−0.024	0.079	0.140	0.026	0.287
Math anxiety in exams	−0.054	−0.113	0.006	−0.236	0.030	0.076
Desire to know (R^2=0.084)						
Anxiety regarding mathematical learning	−0.027	−0.063	0.010	−0.180	0.018	0.149
Self-efficacy	0.106	−0.034	0.250	0.186	0.071	0.136

R^2, regression coefficient of determination; B, regression coefficient; CI, confidence interval; β, adjusted coefficient from multiple linear regression analysis; SE, coefficient standard error.

TABLE 4 Multiple linear regression models for the dimensions of the mathematics attitudes (dependent variable) in females.

Independent variables	*B*	CI (95%)		β	SE	*p*
		Lower bound	Upper bound			
Anxiety (R^2=0.574)						
Anxiety in mathematical learning	−0.224	−0.277	−0.170	−0.565	0.027	<0.001
Math anxiety in exams	−0.137	−0.223	−0.052	−0.215	0.043	0.002
Self-efficacy	0.236	0.078	0.394	0.134	0.080	0.004
Pleasure (R^2=0.263)						
Anxiety in mathematical learning	−0.094	−0.116	−0.073	−0.512	0.011	<0.001
Utility (R^2=0.154)						
Anxiety in mathematical learning	−0.089	−0.117	−0.060	−0.392	0.014	<0.001
Motivation (R^2=0.149)						
Anxiety in mathematical learning	−0.040	−0.054	−0.027	−0.386	0.007	<0.001
Confidence (R^2=0.201)						
Anxiety in mathematical learning	−0.057	−0.079	−0.036	−0.500	0.011	<0.001
Self-efficacy	0.118	0.055	0.181	0.232	0.032	<0.001
Math anxiety in exams	0.039	0.005	0.073	0.212	0.017	0.024

R^2, regression coefficient of determination; B, regression coefficient; CI, confidence interval; β, adjusted coefficient from multiple linear regression analysis; SE, coefficient standard error.

TABLE 5 Multiple linear regression models for the dimensions of the statistics attitudes (dependent variable) in female.

Independent variables	*B*	CI (95%)		β	SE	*p*
		Lower bound	Upper bound			
Safety (R^2=0.316)						
Anxiety in mathematical learning	−0.237	−0.285	−0.189	−0.526	0.024	<0.001
Importance (R^2=0.111)						
Anxiety in mathematical learning	−0.075	−0.104	−0.046	−0.334	0.015	<0.001
Utility (R^2=0.063)						
Math anxiety in exams	−0.068	−0.104	−0.032	−0.252	0.018	<0.001
Desire to know (R^2=0.107)						
Anxiety in mathematical learning	−0.054	−0.075	−0.032	−0.327	0.011	<0.001

R^2, regression coefficient of determination; B, regression coefficient; CI, confidence interval; β, adjusted coefficient from multiple linear regression analysis; SE, coefficient standard error.

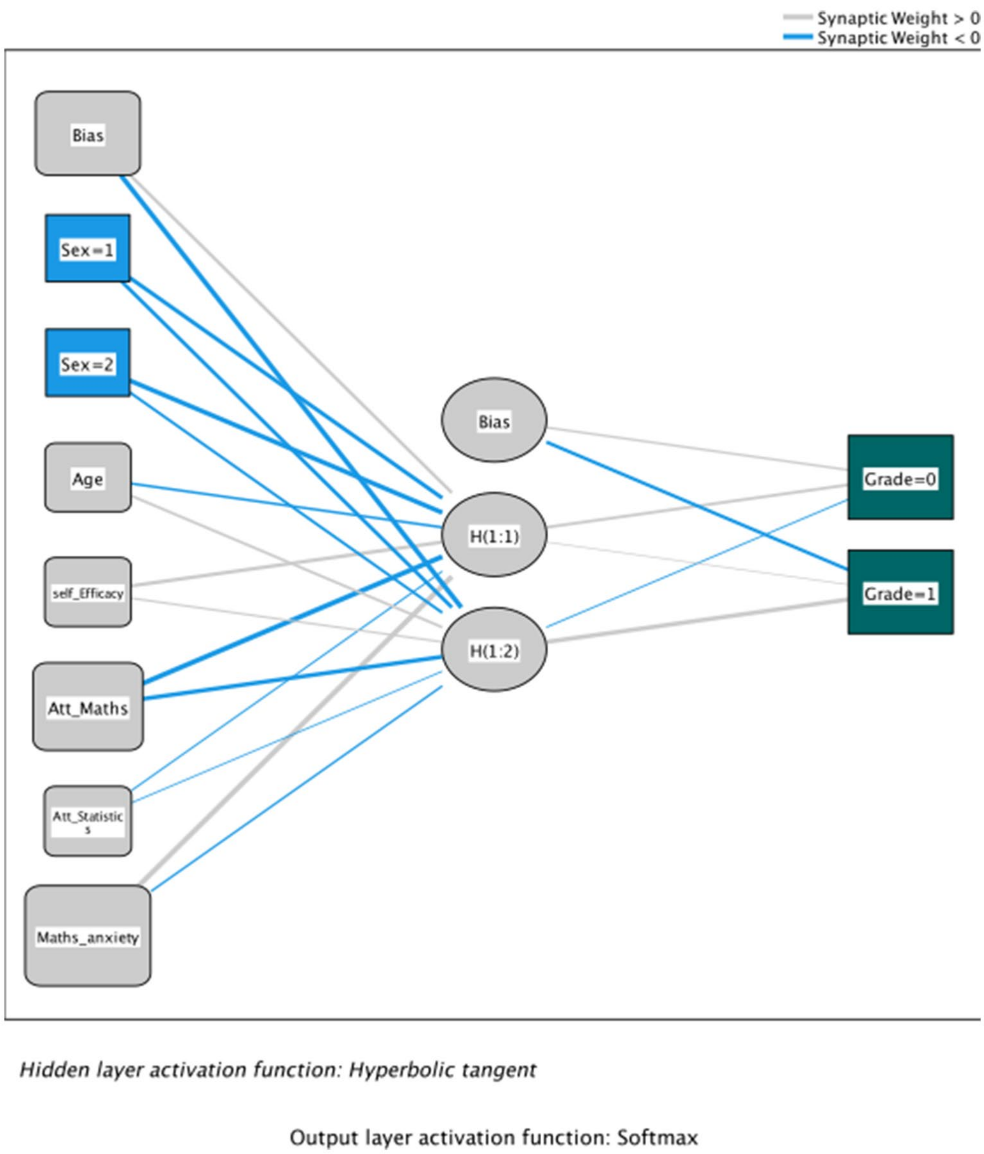

FIGURE 5
Academic performance: Proposal of an artificial neural network based on self-efficacy, mathematics and statistics attitudes, mathematical anxiety, and sociodemographic variables.

TABLE 6 Estimated parameters of the artificial neural network.

Predictor		Predicted			
		Hidden layer 1		Output layer	
		H(1:1)	H(1:2)	[Grade=0]	[Grade=1]
Input layer	(Bias)	0.305	−0.635		
	[Sex=1]	−0.362	−0.357		
	[Sex=2]	−0.602	−0.272		
	Age	−0.176	0.248		
	Self-Efficacy	0.323	0.140		
	Att_Maths	−0.716	−0.433		
	Att_Statistics	−0.127	−0.019		
	Math_anxiety	0.804	−0.143		
Hidden layer 1	(Bias)			0.166	−0.314
	H(1:1)			0.299	0.016
	H(1:2)			−0.059	0.580

Sex=1, female; Sex=2, male; Att_Maths, mathematics attitudes; Att_Statistics, statistics attitudes; Grade=0: Q2, Q3 y Q4 within academic performance; Grade=1: Q1 or academic excellence.

TABLE 7 Clasification.

Example	Observed	Predicted		
		Academic performance Q2, Q3 y Q4	Performance of excellence (Q1)	Correct percentage
Training	Academic performance Q2, Q3 y Q4	135	0	100.0%
	Performance of excellence (Q1)	52	0	0.0%
	Overall percentage	100.0%	0.0%	72.2%
Testing	Academic performance Q2, Q3 y Q4	46	0	100.0%
	Performance of excellence (Q1)	11	0	0.0%
	Overall percentage	100.0%	0.0%	80.7%
Holdout	Academic performance Q2, Q3 y Q4	27	0	100.0%
	Performance of excellence	4	0	0.0%
	Overall percentage	100.0%	0.0%	87.1%

Dependent variable: academic excellence.

When analyzing the importance of the independent variables (Table 9 and Figure 9), "mathematics anxiety" was found to be the variable that contributed the most to the predictive capacity of the model, followed by "attitudes toward mathematics" and "attitudes toward statistics." The sociodemographic variable "sex" barely contributed to predictive capacity.

4. Discussion

This study examined the relationship between different aspects of mathematics learning and statistics representing every student. To keep them in mind, we refer to the dimensions above explained of mathematics anxiety, mathematics and statistics attitudes, and finally self-efficacy.

As mentioned at the beginning of this study, some relationships were expected regarding the influence of these variables that are part of the affective-emotional domain on attitudes toward mathematics, in the same way as in the previous study by Xiao and Sun (2021) in which the negative impact of mathematical anxiety on attitudes related to mathematics was evidenced, with students with higher levels of mathematical anxiety being less persistent in the study and with lower academic performance. It was also expected to find, in general terms, the positive relationship between self-efficacy and those attitudes in coherence with the study conducted by Czocher et al. (2020) in which positive correlations were also found between the levels of self-efficacy and the degree of motivation and persistence in studying them.

In this sense, it is important that future teachers are trained to consider not only the cognitive components but also the affective domain so relevant for the teaching/learning process of mathematics as stated in different studies (García-Suárez et al., 2023; Spencer et al., 2023).

4.1. Relationship between sex and study variables

Self-efficacy levels are quite similar among males and females in our research. Considering that the maximum level that could be reached was 40, the people asked were themselves thought to be capable of facing a wide range of situations and having tools to solve them properly. Specifically, the average level for the sample was

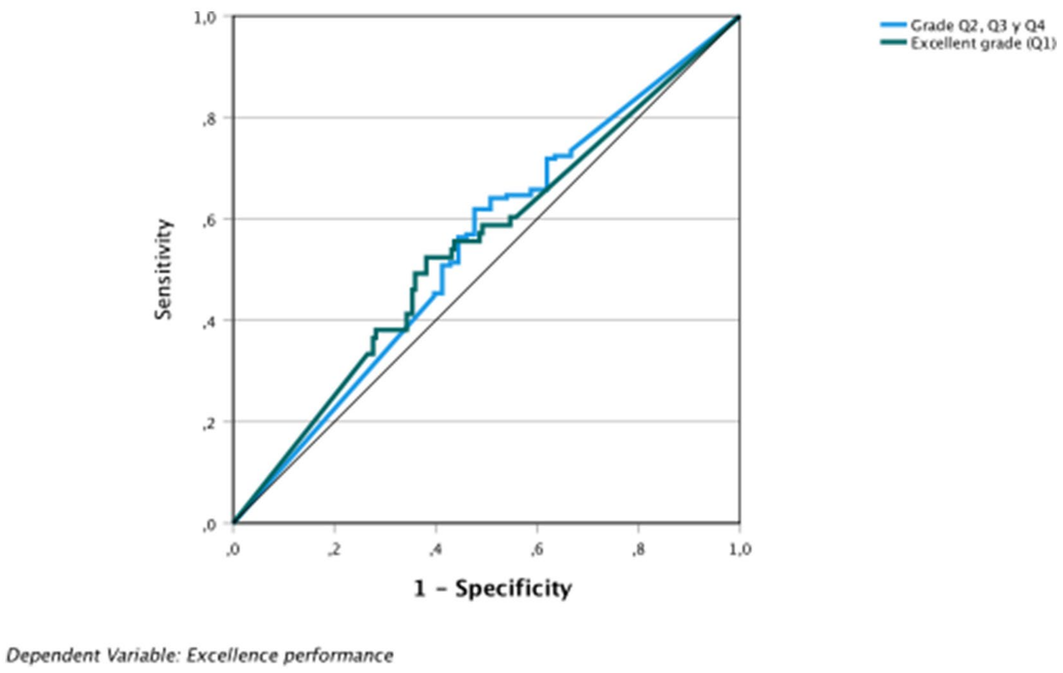

FIGURE 6
Dependent variable: academic excellence: especificidad.

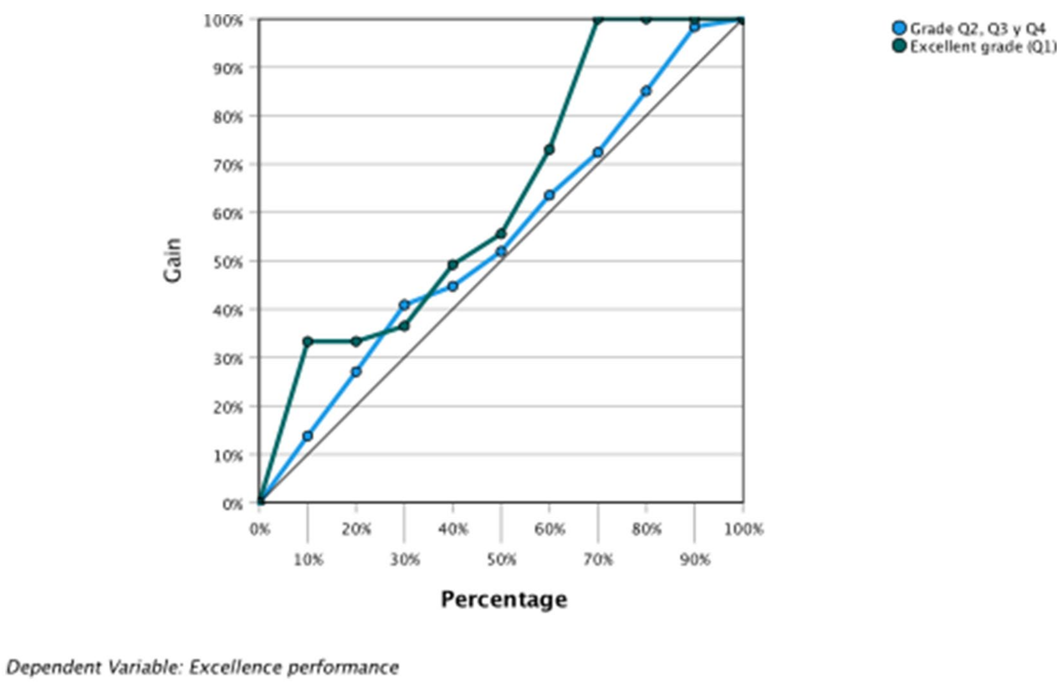

FIGURE 7
Dependent variable: academic excellence. Porcentages ganancia.

29.590, which is a high level according to the scale. In addition to that, there is no significant difference between both populations. In the previous study by Abín et al. (2020) significant differences were found according to sex, even considering that the differences were due to the role played by this variable rather than due to the effects of affective and motivational variables. Also, in a recent investigation (Ryan et al., 2022), different levels of mathematical self-efficacy were found as a function of gender. In contrast, in another study, no statistically significant gender differences were found in the self-efficacy variable (Smith et al., 2010). It would be interesting to

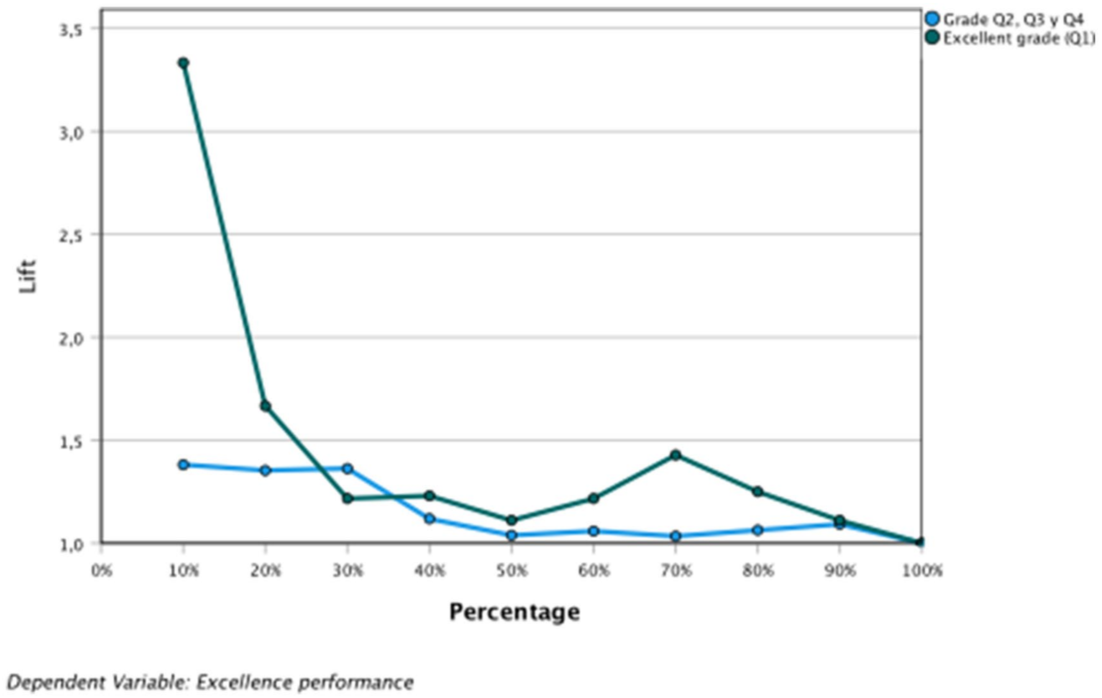

FIGURE 8
Dependent variable: academic excellence. Porcentages elevation.

TABLE 8 Area under the curve.

		Areas
Academic excellence (Grade)	Academic performance Q2, Q3 y Q4	0.545
	Performance of excellence (Q1)	0.544

TABLE 9 Independent variable importance.

	Importance	Normalized importance
Sex	0.001	0.2%
Age	0.029	5.2%
Self-efficacy	0.035	6.3%
Mathematics attitudes	0.341	61.9%
Statistics attitudes	0.045	8.3%
Mathematical anxiety	0.550	100.0%

Dependent variable (VD): Grade.

continue to administer even more specific instruments for the evaluation of this variable in the cultural context in which this study is conducted.

Regarding mathematics attitudes, there was a significant difference between males and females. In fact, males showed a slightly higher level of mathematical attitudes than females. This could be due to several reasons, such as some stereotypes present in the sciences in general, and in mathematics in particular, as stated in Ghazvini and Khajehpour (2011), Rodríguez et al. (2020), and Froehlich et al. (2022). For statistical attitudes, unlike before, there was no significant difference between males and females in this research. This result is congruent with previous studies in which no gender differences in attitudes toward statistics are found (Gil-Flores, 1999; Mondéjar et al., 2007). It seems that it is the previous experience in some way related to statistics, such as having books on this subject at home or having read some of these books, which is most related to the positive attitudes shown toward statistics, especially in terms of liking it (Vilà and Rubio, 2016). This can be explained by an argument regarding utility. In other words, as statistics are, in general, less abstract than other mathematics branches and, as a consequence, more applied to other fields, it is generally more appealing to students.

Finally, there was a significant difference in mathematics anxiety between males and females in our research. In general, the level of state-anxiety is higher in women compared to men (Montero and Morales-Rodríguez, 2021). More specifically, recent research shows higher levels of math anxiety in females compared to males (Rončević Zubković et al., 2021). Other papers also find statistically significant gender differences in levels of math anxiety, with females presenting higher levels (Paechter et al., 2017; Ryan et al., 2022). As previously stated, Ghazvini and Khajehpour (2011), Özcan and Eren Gümüş (2019), Li et al. (2021), Rovan et al. (2022), and Ryan et al. (2022) treat this situation and provide some possible reasons. In this sense, some of the relevant factors that can be highlighted are the training and previous knowledge in this subject by the students, which can be related to the levels of anxiety and stress they show (Vilà and Rubio, 2016).

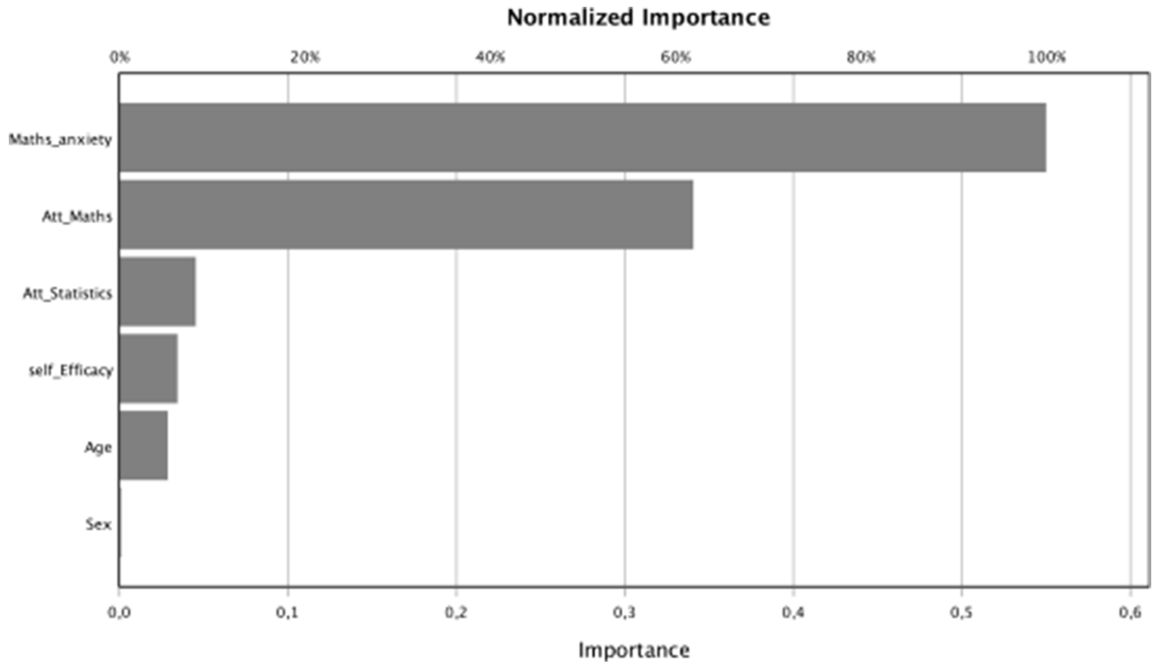

FIGURE 9
Independent variable: importance.

4.2. Relationship between mathematics and statistics attitudes and study variables

For both mathematics and statistics attitudes, there was a similar pattern of influence on mathematics anxiety and self-efficacy in the present study. As expected, in most cases, the influence of mathematical anxiety was mainly negative, which seems plausible and logical if considered Mathematical Anxiety can be interpreted as aversion to mathematics in any form (Li et al., 2021; Ryan et al., 2022). In fact, the dimensions of this kind of anxiety studied here involve many aspects of a student's life, from daily activities such as buying clothes to taking a mathematics test being as García et al. (2016) indicates higher levels of anxiety when facing an exam or trying to understand a mathematical problem in class before other situations of everyday life in which Mathematics is continuously being applied. The influence of this type of anxiety on students' learning results in, as previously mentioned, an aversion and a false feeling of incapability in any mathematical knowledge, pygmalion effect, and a less positive mathematical self-concept (Rončević Zubković et al., 2021). Besides, The students with lower levels of mathematical anxiety were found to have higher motivation and performance compared to other motivational profiles with higher levels of anxiety (Xiao and Sun, 2021). The study by Rovan et al. (2022) also indicates that motivational beliefs are a predictor variable of mathematics anxiety in prospective teachers. In another recent research, García-Suárez et al. (2023) show the relationship between the mathematical anxiety construct and the greater presence of negative attitudes and their consequences for the learning of this subject. It can also be noted that, as found by Paechter et al. (2017), it can be expected that levels of anxiety toward mathematics can be expected to correlate positively with levels of statistical anxiety.

However, the opposite was observed in the self-efficacy dimension. In all cases where this dimension is significant, the effect produced can be categorized as positive. A positive evaluation of this dimension may be crucial in terms of the capability to face and solve problems (Chen et al., 2023; Poçan et al., 2023; SalehAlabdulaziz, 2023; Samuelsson, 2023). It is also a predictor variable that has been considered relevant for motivation and persistence for the so-called STEAM careers and hence the need to contribute to its improvement from different educational levels (Czocher et al., 2020). These data obtained in our study are congruent with other research in which levels in the variable self-efficacy were found to be related to students' levels of math anxiety and academic motivation (Özcan and Eren Gümüş, 2019). Recently, García-Suárez et al. (2023) found inverse correlations between the variable's math anxiety and perceived degree of self-confidence.

4.3. Differences in mathematical anxiety before and after a mathematics exam

The results showed that levels of mathematical anxiety decreased after the completion of a mathematics test. This can be understood as a sensation of freedom and relief that appeared after the exam was completed. However, this sensation is supposed to be transient as worries appear again when students face mathematics lessons. The academic setting is one of those that can generate daily stress in young people (Elsalem et al., 2020; Morales-Rodríguez, 2021) and, like the current study, in the work of García et al. (2016), it is mentioned that the university students participating in their research show less anxiety toward mathematics in their daily lives compared to when they try to understand mathematical problems, or when they sit for evaluations or exams corresponding to the mathematics subjects they take in their academic training.

4.4. Relationship between academic performance and mathematical anxiety and mathematical and statistics attitudes: proposal of an artificial neural network based on self-efficacy, mathematics and statistics attitudes, mathematical anxiety, and sociodemographic variables

The results showed that mathematical anxiety had a crucial paper in the classification in terms of academic performance. In addition to that, mathematical attitudes had also a significant role in the classification. On the other hand, statistical attitudes did not have such importance, but a lesser important impact. The relations, as it is stated in the introduction, are then accepted by the results obtained as evidenced in studies such as those conducted by Xiao and Sun (2021). Geisler et al. (2023) also highlight the existence of relationships between attitudes toward mathematics and the academic achievement variable. Orbach et al. (2019) also find inverse correlations between components of the math anxiety and academic performance variables. In the same line, another research found that anxiety levels and motivation in that order were predictor variables of the performance variable (Suren and Kandemir, 2020). Spencer et al. (2023) found that self-efficacy was also a predictor variable of overall course grade. In our study, the results obtained have been confirmed using the fundamentals of a classical methodology based on regression analysis and, especially, with the innovative design of artificial neural networks, which have proven to be very useful in the field of educational psychology (Hwang et al., 2020; Martínez-Ramón et al., 2021). This confirmation with this type of analysis based on artificial intelligence to the educational field, was much needed in this field of knowledge since there were still results that did not find effects of self-efficacy improvement on academic performance (Gamlem et al., 2019), or that consider the existence of contradictory results regarding the relationships between attitudes toward mathematics such as interest and academic performance (Rach and Heinze, 2017).

4.5. Implications for education

Several studies have demonstrated the implications of mathematics anxiety in the learning process. The present research is also one of these, since mathematics and statistics attitudes are crucial to the learning process mentioned above. In this sense, we could emphasize the implications of this research for the advancement of educational psychology by contributing in some way with a new analysis based on artificial intelligence models to further clarify the relationships between constructs related to the affective-emotional dimension of attitudes toward mathematics such as mathematical anxiety and self-efficacy with student motivation and academic achievement. To date, regression models had been applied using structural equations in which there were still inconclusive or contradictory data. Thus, we are trying to contribute to generate new knowledge considering another key aspect to highlight the implications of this study in the field of artificial intelligence and artificial neural networks. The development of the neural network designed based on self-efficacy, mathematics and statistics attitudes, mathematical anxiety, and sociodemographic variables is considered useful in the field of educational psychology, as there are many advantages that the advances in artificial intelligence can bring to the analysis of the relationships between the constructs evaluated here and educational decision-making (Colchester et al., 2016; Guo et al., 2021; Martínez-Ramón et al., 2023). The levels of math anxiety, self-efficacy and sociodemographic variables of the study contributed to the predictive capacity of the artificial neural network of the variable academic performance in this subject.

Mathematical and statistical skills, such as information arrangement and interpretation, are key points in modern society. As we are exposed to uncountable information sources, the process of learning mathematics becomes a recurrent issue when reforms of the educational system are discussed. Precisely in Spain, these aspects are being debated in Early Childhood Education in view of the changes in the curriculum due to new legislative provisions such as the Royal Decree 95/2022, of February 1 (Royal Decree, 2022), which establishes the organization and minimum teachings of Early Childhood Education. Likewise, the LOMLOE (2020) (Organic Law 3/2020, of December 29, which modifies Organic Law 2/2006, of May 3, on Education) places special emphasis on affective-emotional education and the prevention of gender stereotypes within the Mathematics curriculum. Therefore, teacher training in this area is essential to contemplate the design of learning situations that work on emotional competence in related areas and STEAM careers.

Dimensions such as motivation or confidence should be considered in the design of experiences, activities, and didactical units. Thus, the inclusion of new technologies, such as smartphones, personal computers, and other devices, might be interesting, as presented by Plenty and Heubeck (2013), Turel and Sanal (2018), and Watt et al. (2019). In this sense, it should be noted that the use of Information and Communication Technologies with the design of e-learning courses, mobile applications to clarify doubts and difficulties in the teaching/learning process of mathematics, sharing daily news and stories of daily life that demonstrate its usefulness and that it is not inert knowledge, with active and interactive methodologies with the use of images (movies, videos, sharing presentations, etc.) and not only words, could contribute to promote the development and acquisition of this affective or emotional dimension in its positive aspect with the improvement of self-efficacy and in its negative aspect with the improvement of self-efficacy and in its positive aspect with the improvement of self-efficacy, videos, sharing presentations, etc. For this, in the didactic planning it would be necessary to train effective coping strategies to reduce anxiety problems in mathematics exams and to improve self-perceived competences that could help to reduce school difficulties or failure. In addition to that, Ren et al. (2016) described a curious experience. This study examined, in a sample of 94 students in a mathematics course at a Turkish University, how the use of an e-book influenced academic performance, motivation, and mathematical anxiety in a group of students compared to another group that used a printed book. In this sense, in a future study, we could also consider how the use of digital materials and even social networks influences university students. This type of resource would be especially motivating for secondary school students. There are already previous studies that show that having books and reading them about statistics can help to improve attitudes toward mathematics and statistics by generating greater interest and enjoyment (Vilà and Rubio, 2016).

Finally, Orbach et al. (2019) focused on the motivational profile of students. This study explored the relationship between this motivational profile and student aspirations. Data from the *Study of Transitions and Education Pathways* (*STEPS*; Watt et al., 2019) can be consulted. In this sense, this type of assessment related to the affective or emotional dimension of attitudes toward mathematics and self-efficacy is necessary especially in STEAM degrees where, as found by Czocher et al. (2020), academic self-efficacy is one of the most important variables for dropout and contributing to motivation in such degrees. This aspect can be considered especially relevant since achievements in the field related to the teaching of Mathematics are also fundamental for the achievement of the Sustainable Development Goals (2023) given its applications so relevant to everyday life in addition to other aspects related to the gender perspective and for the achievement of goal number 5 of the United Nations 2030 Agenda for Sustainable Development (gender equality and empowerment of women and girls). This would allow us to design interventions and teaching planning considering the effect of the gender variable and the already known Vygotskian Zone of Proximal Development also considering that, as indicated in the study by Spencer et al. (2023) an overconfidence with too easy tasks could also have a negative impact on academic performance. It also allows us to reflect on the importance of the tasks that teachers ask of their students for the acquisition or development of competencies and their feedback in the design of learning situations. Self-regulated learning, self-perceived competencies and metacognition need to be enhanced, consistent with what is put forward by Gamlem et al. (2019) and Özcan and Eren Gümüş (2019). The development of adaptive beliefs about this material should also be encouraged from the initial training of future teachers (Rovan et al., 2022), providing them with the necessary training to avoid gender bias in the assessment of attitudes toward mathematics (León-Mantero et al., 2020). This will be very useful to prevent this discriminatory typology from Early Childhood Education and for the construction of the person and the integral development of the personality, considering in this case the affective or emotional dimension of attitudes toward mathematics in coherence with the LOMLOE. We believe that these aspects can contribute to the necessary improvement of educational inclusion and attention to motivational diversity without leaving emotional competencies in the Mathematics and Statistics curriculum in the background. For the improvement of motivation in the design of learning situations required by the recent laws in Spain, it is considered very useful the keys that are raised in articles such as Valle et al. (2006). Therefore, the information provided by this type of study is useful for vocational guidance of students from secondary education and encourages women to enroll more in degrees such as Mathematics considering these aspects and the importance of improving training and experiences with mathematics and statistics at these educational levels.

4.6. Limitations and future research directions

This research could lead to other similar research, as the influence of anxiety on the learning process is an interesting topic. In addition, mathematics has always been a special subject; it is considered a difficult and incomprehensible branch of knowledge, and experts have tried to make it accessible to the majority of the population. For this purpose, the effects of anxiety on the learning process could be studied further and some solutions could be proposed. In addition, activities to improve mathematics and statistics attitudes could be proposed and tested, as these attitudes are important in terms of the predisposition to learn and comprehend. Further studies could include the insertion of these studies and predictions into recently proposed skill-based learning and how the levels of attitudes and anxiety evolve under this type of learning.

One limitation of this study was the sample size in one of its groups, such as the need to continue expanding the sample of secondary education students in more centers, even analyzing differences between centers in rural and urban contexts so that the information can be generalized to other cultures and language registers since the current sample was made up of Spanish-speaking students. On another note, the area under the curve obtained in the ANN also leads to be cautious in its analysis although it has a predictive capacity above chance.

In future studies, it would also be interesting to analyze the affective domain such as anxiety toward mathematics not only in future teachers and students, but also in the other element of the educational situation such as teachers who already teach mathematics. In this sense, in the case of secondary education teachers of mathematics, it has been found that the main situations generating emotional feelings in Mexican teachers were the attitudes of commitment, motivation and the academic performance of their students. Emotions such as pride, gratitude, appreciation, and happiness appeared in the face of student learning, and academic achievement. Non-commitment and low academic motivation generated in teachers' emotions such as anger, disappointment or reproach (Martínez-Sierra et al., 2022). It would also be interesting to test the effect that the variables cognitive flexibility and creativity, which are predictive of positive attitudes toward mathematics, may have on attitudes toward mathematics in future teachers (De la Peña et al., 2021). In this way, we would not be leaving aside the cognitive domain of mathematics so that, as proposed by De la Peña et al. (2021), we could try to introduce elements of innovation for the improvement of creativity and divergent thinking with implications for the planning of the practical teaching of mathematics that could result in more positive attitudes. Evaluations could also be applied with other more recent instruments even more specifically adapted to the Spanish context for the evaluation of attitudes toward mathematics, such as considering the importance of each item in the factorial estimation by means of a structural equation analysis (León-Mantero et al., 2020) or by means of one of the methods recently considered among the most effective for analyzing the psychometric properties of an instrument, such as the Rash model (Morales-Rodríguez et al., 2021). It would also be interesting to further evaluate cross-cultural variations for comparing different regions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by The Ethics Committee of the University of Granada (Granada, Spain, 3376/CEIH/2023). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

FM-R led, conceived and designed the study, contributed to the bibliographic review, recruited the participants, and contributed to the manuscript writing and data analysis. JH and JM-R contributed to the manuscript writing, and data analysis. JR-G recruited the secondary school students and contributed to the manuscript writing. All authors revised the manuscript critically and approved the final version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer CR declared a shared affiliation with the authors JM-R to the handling editor at the time of review.

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Perceived parental involvement influences students' academic buoyancy and adaptability: the mediating roles of goal orientations

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Academic buoyancy and adaptability (i.e., student capacities to deal with difficulties and challenges in daily school lives and to make appropriate cognitive, behavioral as well as affective adjustments in interacting with new, uncertain, and/or changing situations, circumstances, and conditions) can help learners regulate and protect themselves in the failure-prone learning environment. This study examined how students' perceptions of parental academic involvement and their goal orientations were related to their academic buoyancy and adaptability in mathematics learning. We recruited a sample of 1,164 Chinese junior high school students. Using structural equation modeling, the results indicated that after controlling for family socioeconomic status and gender, perceived parental involvement was positively related to the students' academic buoyancy and adaptability. Furthermore, parental involvement was significantly associated with students' mastery and performance-approach goal orientations, which further partially mediated the relationship between parental involvement and academic buoyancy and adaptability. However, the mediating role of a performance-avoidance goal orientation in this relationship was not significant. Findings highlight the important roles that parenting practices and individual achievement motivation play in the development of academic buoyancy and adaptability in the Chinese context. Future research directions and implications are discussed.

KEYWORDS

academic buoyancy, adaptability, goal orientations, parental involvement, mathematics learning

Introduction

A vast majority of students may encounter difficulties, challenges, changes, and uncertainties throughout their daily school lives, which calls for day-to-day coping abilities. In the subject of mathematics, the complexity of mathematical formulae, concepts, and theorems means that negative attitudes toward maths are common among learners worldwide (OECD, 2013). Despite the many endeavors that have been made to address maths anxiety and avoidance, building positive behaviors and beliefs before negativity emerges may be more productive (Lee and Johnston-Wilder, 2017). Deriving from the field of positive psychology, academic buoyancy and adaptability are two kinds of capacities that can help learners regulate and protect themselves from adverse events or complex situations that arise in a relatively failure-prone learning environment (Collie et al., 2017; Martin and Marsh, 2020). These abilities in maths learning may influence students' mathematics performance and psychological well-being in later life, thus it is crucial to understand the antecedents of academic buoyancy and adaptability.

Students' learning skills have been found to be influenced by learning motivation (Hsieh, 2014; Schukajlow et al., 2017). Goal theory (Nicholls, 1984; Ames, 1992), a dominant theoretical perspective on students' achievement motivations, explains why and how people seek to achieve different goals, including mastery, performance-approach, and performance-avoidance orientations. It provides a framework for studying the contribution of goal orientation to students' ability to achieve. Although goal orientations have received much attention among educational researchers, few empirical studies have related goal orientations to academic buoyancy and adaptability. To address these research gaps, this study examines the effect of goal orientations on academic buoyancy and adaptability.

Environmental factors can influence both what individuals think and what they do (Schunk and Zimmerman, 2006). Parenting as a crucial home-environment variable may have a salient impact on child development. Darling and Steinberg (1993) developed a contextual model of parenting and posited the linkage between adolescents' perceptions of parental practices and adolescents' learning profiles. Based on this model, the present study focused on parents' involvement in mathematics learning and assumed that students' perceived parental involvement may influence their goal orientations, academic buoyancy and adaptability.

Academic buoyancy and adaptability

In educational research (e.g., Li et al., 2017; Sattler and Gershoff, 2019; Wills and Hofmeyr, 2019), much attention has been paid to exploring why some students are successful in school despite experiencing major adversity. This research has produced the well-known concept of academic resilience. A related concept, academic buoyancy, similarly denotes a student's ability to deal with difficulties and challenges. Compared with resilience, however, buoyancy is more closely related to how students handle daily stressors that a vast majority of students may suffer from, such as urgent deadlines, difficult homework, examination pressure, and unexpectedly or consistently receiving low grades (Martin and Marsh, 2008, 2009). In addition to major adversity (requiring resilience) and everyday challenges and difficulties (requiring buoyancy), new, uncertain, and/or changing circumstances and conditions may arise during learning, leading to the need for another ability, adaptability. According to an early definition by the American Psychological Association, adaptability is "the capacity to make appropriate responses to changed or changing situations; the ability to modify or adjust one's behavior in meeting different circumstances or different people" (VandenBos, 2007, p. 17). With subsequent research advancements, this concept now includes the ability to make appropriate cognitive, behavioral, and affective adjustments (Martin, 2012; Martin et al., 2012, 2013), or in other words, the ability to adjust one's thoughts, behaviors, and emotions to navigate new, uncertain, and changing demands.

When examining the development of academic buoyancy and adaptability, it is necessary to consider the cultural values in individual societies. In China, owing to the collectivistic–Confucian cultural tradition, education is perceived as the main means of achieving personal growth and knowledge expansion. Most Chinese parents hope that their children will have a bright future, and are willing to make sacrifices for their children's education (Lee and Morrish, 2012), and many students agree that academic success can bring honor to the family and repay the parents' sacrifice and investment (Hau and Salili, 1996; Leung, 2020). Influenced by Confucianism's belief that diligence, intrinsic motivation, and willpower are more important to personal success than individuals' innate ability, even though Chinese students have to contend with increasing academic burdens and psychological pressure in competitive academic life, they tend to have high levels of academic buoyancy and adaptability. Considering most of the existing literature base was established in the Western world, the current research aims to generalize the findings of academic buoyancy and adaptability to Confucian culture societies.

The effect of parental involvement on academic buoyancy and adaptability

Parental involvement in education, also called parental academic involvement, is defined as parents' engagement with their children's schools and involvement with their children's learning to promote their educational success (Hill and Taylor, 2004). It is a multidimensional concept that includes involvement at home, involvement at school, and academic socialization (Fan and Chen, 2001; Hill and Tyson, 2009; Hill et al., 2018). Examples of home-based involvement are assistance with homework and the monitoring of schoolwork and progress. School-based involvement refers to participation in school events and communication with teachers. Academic socialization includes talking to children about schoolwork, their plans, and their goals.

Empirical research has shown that parental involvement can foster student persistence when facing difficulties and challenges (e.g., Wong, 2008; Mena, 2011; Rubach and Bonanati, 2023). For instance, Wong (2008) investigated 171 adolescents in the US to explore the factors that predict students' ability to adapt and succeed despite adverse circumstances. The results showed that greater parental involvement led to more effort to stay in control and to identify regulations, which helped high-risk adolescents increase their resilience. In addition, many researchers have claimed that engaging parents in an effective mode of academic involvement is an important ingredient for the development of children's ability to adjust to learning demands arising from unprecedented and changing situations (e.g., Sheldon and Epstein, 2005; Ratelle et al., 2017; Yu et al., 2022). For example, emergency remote instruction for school learning is newly occurring but general during the COVID-19 pandemic. Yu et al. (2022) investigated the contribution of parental involvement during the special period of school closure and found that parental involvement can facilitate children's learning engagement, which is beneficial for children's academic performance. Although few studies have directly explored the impact of parental involvement on student academic buoyancy and adaptability, the empirical results above made it appropriate to hypothesize the positive relationship. In the present study, we investigate the association between parental involvement and buoyancy and adaptability in the context of mathematics learning and hypothesize goal orientations may mediate this relationship.

The mediating roles of goal orientations in the relationship between parental involvement, academic buoyancy, and adaptability

Goal orientations, as part of individual cognitive life, act as frameworks that guide and give purpose to people's actions (Kaplan and Maehr, 2007). They may reflect a person's experiences, guide their understanding of events, and produce specific modes of cognition, behavior, and emotion (Elliott and Dweck, 1988). Although researchers hold different opinions on the categorization of goal orientations, "mastery" and "performance" are the two terms that are most commonly used. A mastery goal orientation is defined as a focus on developing competence (Ames, 1992), and it has been found to positively predict outcomes in areas such as task values, self-regulated learning and academic achievement (Fadlelmula et al., 2015; Lazarides et al., 2018; Guo et al., 2022). A performance orientation is defined as a focus on demonstrating competence (Ames, 1992). This has been further divided into "performance-approach" and "performance-avoidance" goal orientations due to different findings about the relationship between performance goal orientations and adaptive outcomes (Elliot, 1997; Elliot and Church, 1997; Elliot, 1999). Specifically, a person with a performance-approach orientation tends to care most about demonstrating a high level of competence and being successful, whereas someone with a performance-avoidance orientation tends to focus on how to avoid showing low competence and encountering failure.

Mastery and performance goal orientations are viewed as developing within a person's proximal environment and thus influenced by factors in that environment (Régner et al., 2009; Zheng et al., 2019). Several empirical studies have shown that parental involvement has various consequences for students' different types of goal orientations. For mastery goal orientations, many studies have drawn consistent results about the positive impact of parental involvement (e.g., Duchesne and Ratelle, 2010; Wang et al., 2019; Li et al., 2020). For example, Li et al. (2020) investigated 3,378 Chinese adolescents and found that when they perceived more involvement and autonomy support by parents, they have the higher levels of mastery goals. However, findings about the effect of parental involvement on performance goal orientations are mixed. Luo et al. (2013) used a sample of 1,667 Singaporean students to investigate the role of parenting behaviors in students' development of goal orientations and found that parental involvement in learning modestly and positively predicted students' performance-approach and performance-avoidance goal orientations. Zong et al. (2018) found that parental involvement significantly and positively predicted students' performance-approach goal orientations but had non-significant effects on performance-avoidance goal orientations. Other studies have found a negative correlation between parental involvement and students' performance-avoidance goal orientations (e.g., He et al., 2015). These inconsistent findings suggest that more studies are needed to examine the relationship between parental academic involvement and students' goal orientations.

The effects of different kinds of goal orientations on students' academic progress and outcomes have been examined. Many studies have confirmed the positive effect of mastery goals on student learning. For example, Skaalvik (2018) found that a mastery goal orientation was a strong and direct predictor of the use of problem-focused coping strategies. Additionally, this orientation predicted lower levels of math anxiety and reduced use of self-protective coping strategies, which are conceptualized as maladaptive. Yu and Martin (2014) recruited a sample of 3,753 school children in China and found that mastery goals were positively correlated with students' motivation, engagement, and academic buoyancy. Findings about the relationship between performance goals and adaptive outcomes are inconsistent. Most research has suggested that performance-approach goals can facilitate learning but that performance-avoidance goals inhibit learning (Luo et al., 2013; Mouratidis et al., 2018; Ng, 2018; Möcklinghoff et al., 2023). However, some research has reported that both performance-approach and performance-avoidance goals positively predict academic achievement, engagement, and deep learning strategies (King, 2016), while other researchers have argued that both types of performance orientation underlie a maladaptive response pattern (Dweck, 1986; Lee et al., 2021). Although these inconsistent results mean that the effects of performance goals on student learning are still an open question, they show that goal orientations can predict some coping effects related to academic buoyancy and adaptability. Therefore, it is possible to speculate about the influence of goal orientations on students' academic buoyancy and adaptability. Given the possible relationship between parental involvement and goal orientations and the influence of goal orientations on academic buoyancy and adaptability, we expect the three types of goal orientation partially mediate the hypothesized relationship between parental involvement and academic buoyancy and adaptability.

Influence of control variables

In examining the relationship between parental involvement, goal orientations, academic buoyancy, and adaptability, it is essential to control potentially confounding factors. Researchers have found that family socioeconomic status (SES) has some effects on the degree of parental involvement and that students with a higher family SES perceive greater parental involvement (e.g., Hoff et al., 2002). Moreover, family SES has an effect on students' development of goal orientations (Xu et al., 2020); parental educational level in particular is positively associated with students' mastery and performance-approach goal orientations (Mouratidis et al., 2018). Furthermore, research has shown that a higher family SES seems to be a protective factor when a student is exposed to learning difficulties, so high SES students tend to have greater academic buoyancy and adaptability (Yu et al., 2019). Thus, family SES – obtained by integrating parental education, parental occupation, and family learning resources to give a composite score – is included as a covariate in this study.

Meanwhile, the four variables in the current research have been found to vary depending on gender. Some researchers found that parents were involved in their sons' and daughters' academic learning in significantly different ways, and that girls reported more parental involvement (e.g., Muller, 1998; Shapira-Lishchinsky and Zavelevsky, 2020). Besides, certain gender differences emerged in goal orientations. Boys were more likely to adopt a performance goal orientation (approach or avoidance), while girls were more likely to adopt a mastery goal orientation (D'Lima et al., 2014). Moreover, gender has a significant relationship with academic buoyancy: boys tend to have significantly higher scores for buoyancy than girls (Datu and Yang, 2018). Gender has also been found to have specific effects on affective adaptability, which is a sub-constructs of adaptability, with boys demonstrating greater constructive affective regulation (Martin et al., 2012). Therefore, gender is taken as another covariate in the present study.

The current study

The current research aims to combine the contextual model of parenting with goal theory to test the effects of parental involvement on students' goal orientations, academic buoyancy, and adaptability in the specific context of maths learning in China. Figure 1 depicts a conceptual model summarizing the proposed relationships. Specifically, we propose and test the following hypotheses: (1) parental involvement is a positive predictor of academic buoyancy and adaptability; (2) parental involvement is a positive predictor of mastery goal orientation and performance-approach goal orientation, and a negative predictor of performance-avoidance goal orientation; (3) goal orientations mediate the association between parental involvement and students' academic buoyancy and adaptability.

The study contributes to both theory and practice in the following ways. First, it investigates students' reactions to academic challenges and changes by considering the role of Chinese cultural values and social context. Furthermore, it enriches research by examining the mediational mechanism of students' purposes and behaviors to seek to achieve different goals underlying the links between parental involvement in education and students' coping abilities from a domain-specific perspective. This is still a research gap in the literature. Finally, the research can inform efforts to develop adolescents' academic buoyancy and adaptability and guide policymakers, teachers, and parents in encouraging a deep desire for learning when students are faced with challenges and changes when learning mathematics.

Methods

Participants and procedure

The sample comprises 1,164 students along with their parents/guardians from seven secondary schools in a first-tier city in China. Among the students, 589 (50.6%) were boys and 575 (49.4%) were girls. The selection of schools was based on school principals' willingness to collaborate with the research following their receipt of an invitation letter. Three were boarding schools and four were day schools. In each school, between four and eight classes of eighth-grade classes were randomly selected to complete a survey. All the students and their parents/guardians completed and submitted consent forms before the survey was administered. Once the student and parent/guardian consent had been obtained, the students were asked to fill out a 20-min questionnaire in class, and their parents/guardians were asked to complete a 10-min questionnaire about family SES at home.

Measures

Parental involvement

The Parents' Involvement in Children's Learning Scale (Cheung and Pomerantz, 2011) was used to measure the students' perceived parental involvement. The original scale consisted of 10 items. We modified some items to focus on the subject of mathematics. An example item was "My parents try to get to know the maths teachers at my school". The participants rated the items on a 7-point Likert scale from 1 (strongly disagree) to 7 (strongly agree). A higher score represented greater parental involvement. In the subsequent analysis, according to the cut-off value suggested by Stevens (1992), the factor loading of item 6 was found to be lower than 0.4, so item 6 was excluded. Cronbach's alpha for the modified nine-item scale was 0.877.

Goal orientation

We measured the students' goal orientations based on the Goal Orientation Scale (Midgley et al., 2000). This scale consisted of 14 items. Some were adjusted to concentrate on mathematics learning. Five items focused on mastery goal orientation (e.g., "It's important to me that I learn a lot of new maths concepts this year"). Five items focused on performance-approach goal orientation (e.g., "One of my goals is to show others that I'm good at maths"). Four items focused on performance-avoidance goal orientation (e.g., "It's important to me that I do not look stupid in maths class"). The items were rated using a 7-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). A higher score represented a higher level of goal orientation. The values of Cronbach's alpha for the subscales measuring mastery goal orientation, performance-approach goal orientation, and performance-avoidance goal orientation were 0.915, 0.913, and 0.867, respectively.

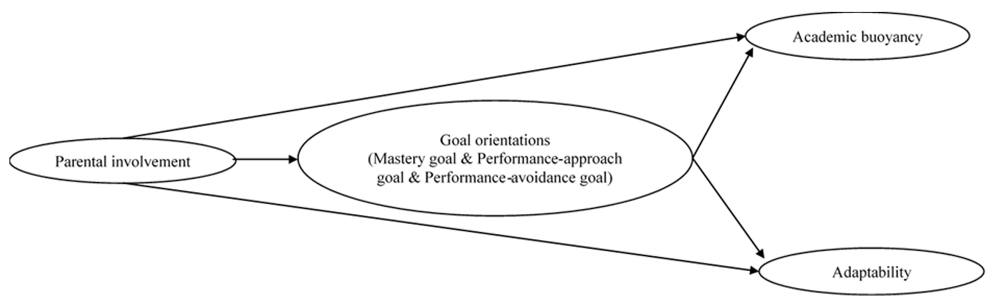

FIGURE 1
Proposed theoretical model of parental involvement, goal orientations, academic buoyancy and adaptability.

Academic buoyancy

The students' academic buoyancy in mathematics learning was measured using the four-item Academic Buoyancy Scale developed by Martin and Marsh (2008). We adjusted the items to concentrate on mathematics learning (e.g., "I do not let the stress of studying maths get on top of me"). The participants rated items using a 7-point Likert scale ranging from 1 (strongly Disagree) to 7 (strongly Agree). A higher score demonstrates greater academic buoyancy. The Cronbach's alpha for this scale was 0.868.

Adaptability

The adaptability scale was adapted from the previously developed Adaptability Scale (Martin et al., 2012, 2013). Six statements focused on cognitive–behavioral adaptability (e.g., "While learning maths, I am able to adjust my thinking or expectations to assist me in a new situation if necessary"), while the other three statements focused on affective adaptability (e.g., "While learning maths, I am able to reduce negative emotions to help me deal with uncertain situations"). The students responded to the items using a 7-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). Higher scores for this measure indicated greater adaptability. Cronbach's alpha for this scale was 0.931.

Student gender and family SES

Student gender (0 = female; 1 = male) and family SES were included in the investigation. Family SES was reported by the parents or guardians, and included parental education, parental occupation, and family learning resources. Parents' education level was measured by collecting data on the highest level of education completed (e.g., 0 = no education, 1 = elementary school, 2 = junior high school, and 3 = high school). Parents' occupation was determined according to information about the occupation and job category provided by the participants. Based on the Chinese Occupational Prestige Measuring Index (COPMI; Li, 2005), we categorized occupations and jobs into seven levels, and individuals at the same level were given identical scores (with scores ranging from 7 to 1). The highest level included occupations such as engineer and university teacher, and the lowest level included jobs such as porter and nanny. The maximum of the mother's and the father's educational (or occupational) score was viewed as the score of the parents' education (or occupation). Besides, the participants needed to report the family resources for student learning, such as the availability of a desk at home to study at, the student's own room, and online maths course resources. We first obtained a summary index of family learning resources by calculating standardized z-scores; we then subjected the parental education, parental occupation, and family learning resources to factor analysis using the principal component method of extraction to determine an aggregate score for family SES. A higher score demonstrated a higher family SES.

Analyses overview

In the hypothesized model, the independent variable was parental involvement. The mediating variables were the three types of goal orientation. The dependent variables were academic buoyancy and adaptability. Student gender and family SES were the two control variables. Descriptive statistics and correlations of all the variables were obtained using SPSS 21.0 software.

A two-step method was used to test the hypothesized model in Mplus 7.4. First, we conducted confirmatory factor analysis (CFA) to confirm the factorial structures of the scales measuring parents' involvement in children's learning, goal orientations, academic buoyancy, and adaptability (Wang and Wang, 2012). The measurement model was a six-factor model consisting of parental involvement, mastery goals, performance-approach goals, performance-avoidance goals, academic buoyancy, and adaptability. All six factors were allowed to relate to each other. Second, structural equation modeling (SEM) was used to assess the mediation. We tested the indirect effects by conducting bootstrap analyses with 95% confidence intervals (bootstrap replications: 1,000) (Preacher and Hayes, 2008). Confidence intervals not containing 0 indicated significant mediated effects. The full information maximum likelihood method was used to handle missing values (Schlomer et al., 2010). The model was considered an adequate fit based on the following indices: the root mean square error of approximation (RMSEA) and standardized root mean square residual (SRMR) were all less than 0.08 and the Tucker-Lewis index (TLI) and comparative fit index (CFI) were all greater than 0.90 (Schermelleh-Engel et al., 2003). All the loading values of the items on the latent factors were required to be higher than 0.4.

Results

Descriptive statistics and correlations

Table 1 shows the descriptive statistics and correlations between the study variables. Both academic buoyancy and adaptability were positively related to parental involvement ($r = 0.301$ and $r = 0.399$, $p < 0.001$, respectively), mastery goals ($r = 0.447$ and $r = 0.557$, $p < 0.001$, respectively), and performance-approach goals ($r = 0.143$ and $r = 0.192$, $p < 0.001$, respectively). Parental involvement was positively associated with mastery goals ($r = 0.355$, $p < 0.001$) and performance-approach goals ($r = 0.119$, $p < 0.001$). Gender was positively correlated with performance-approach goals ($r = 0.125$, $p < 0.001$), performance-avoidance goals ($r = 0.093$, $p < 0.01$), academic buoyancy ($r = 0.217$, $p < 0.001$), and adaptability ($r = 0.207$, $p < 0.001$). Family SES was positively associated with parental involvement ($r = 0.250$, $p < 0.001$), mastery goals ($r = 0.071$, $p < 0.05$), academic buoyancy ($r = 0.100$, $p < 0.001$), and adaptability ($r = 0.100$, $p < 0.001$), but negatively associated with performance-approach goals ($r = -0.089$, $p < 0.01$) and performance-avoidance goals ($r = -0.128$, $p < 0.001$).

Testing the measurement model

When the measurement model was tested using six factors related to their observed indicators, the CFA results showed that χ^2 (576) = 2994.064, CFI = 0.916, TLI = 0.908, RMSEA = 0.060 and SRMR = 0.055, indicating a good model fit for the four scales. Moreover, the standardized factor loadings of each indicator on the corresponding latent construct were all above 0.4 and significant at the $p < 0.001$ level, suggesting that the observed indicators were strongly loaded on their respective latent variables.

TABLE 1 Descriptive statistics and correlation results of study variables (N = 1,164).

	1	2	3	4	5	6	7	8
1 Gender	–							
2 Family SES	−0.023	–						
3 Parental involvement	−0.027	0.250***	–					
4 Mastery goal	−0.004	0.071*	0.355***	–				
5 Performance-approach goal	0.125***	−0.089**	0.119***	0.139***	–			
6 Performance-avoidance goal	0.093**	−0.128***	−0.044	−0.022	0.628***	–		
7 Academic buoyancy	0.217***	0.100***	0.301***	0.447***	0.143***	−0.017	–	
8 Adaptability	0.207***	0.100***	0.399***	0.557***	0.192***	0.004	0.793***	–
M	0.51	0.000	5.061	5.994	3.561	3.452	5.111	5.182
SD	0.500	1.000	1.186	1.005	1.416	1.399	1.348	1.157

*p < 0.05, **p < 0.01, ***p < 0.001.

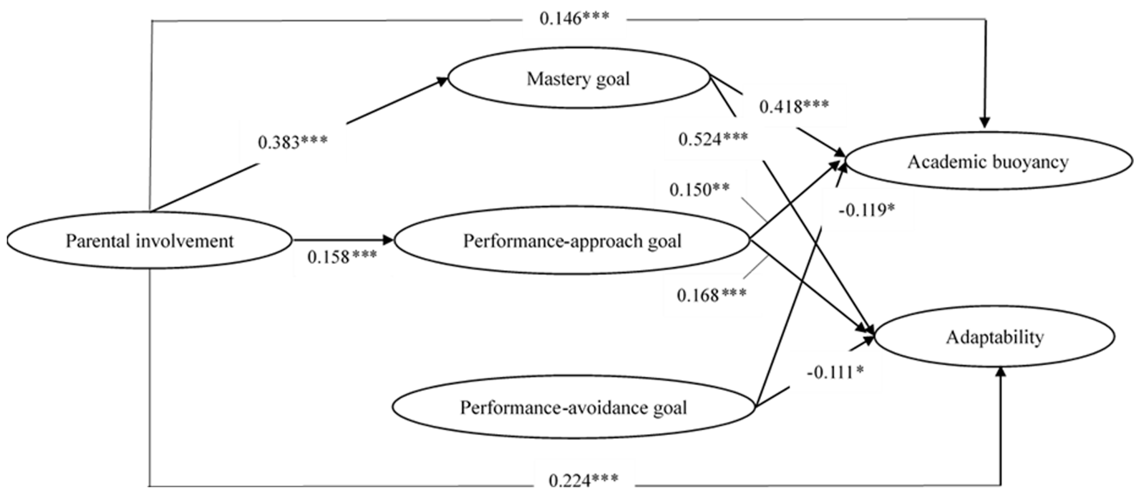

FIGURE 2
Structural equation model testing the relationship between parental involvement, goal orientations, academic buoyancy, and adaptability. To simplify the view, we do not show the observed indicators of each latent variable in the figure. All the correlations and path coefficients shown in the figure are standardized and statistically significant (*p < 0.05, **p < 0.01, ***p < 0.001).

Examining the structural model

The SEM results are presented in Figure 2 and demonstrate an acceptable model fit: χ^2 (711) = 3318.021, CFI = 0.912, TLI = 0.903, RMSEA = 0.056, SRMR = 0.053. The total R squares for academic buoyancy and adaptability were 0.356 and 0.529, respectively. Table 2 shows the standardized estimates and 95% confidence intervals of both direct and indirect paths. The direct path between parental involvement and academic buoyancy was significant (β = 0.146, p < 0.001). The mediation effect of a mastery goal orientation between parental involvement and academic buoyancy was 0.160 (p < 0.001), indicating that a mastery goal orientation had a partial positive mediating effect on the correlation between parental involvement and academic buoyancy. The mediation effect of a performance-approach goal orientation between parental involvement and academic buoyancy was 0.024 (p < 0.05), indicating that the performance-approach goal orientation had a partial positive mediating effect on the correlation between parental involvement and academic buoyancy. The mediation effect of the performance-avoidance goal between parental involvement and academic buoyancy was not significant (β = 0.000, p > 0.05), indicating that the performance-avoidance goal did not mediate between parental involvement and academic buoyancy. Parental involvement explained 33% of the variance of academic buoyancy. Indirect links accounted for 55.8% of the relationship between parental involvement and academic buoyancy, with a stronger link through mastery goals (48.5%) than through performance-approach goals (7.3%).

TABLE 2 The results of the bootstrap analysis ($N = 1{,}164$).

Paths	β	95% CI	
		Low	High
Parental Involvement – Academic Buoyancy	0.146***	0.059	0.222
Parental Involvement – Mastery Goal – Academic Buoyancy	0.160***	0.113	0.207
Parental Involvement – Performance-Approach Goal – Academic Buoyancy	0.024*	0.007	0.047
Parental Involvement – Performance-Avoidance Goal – Academic Buoyancy	0.000	−0.010	0.011
Total effect	0.330***	0.256	0.402
Parental Involvement – Adaptability	0.224***	0.139	0.298
Parental Involvement – Mastery Goal – Adaptability	0.201***	0.149	0.257
Parental Involvement – Performance-Approach Goal – Adaptability	0.027**	0.011	0.050
Parental Involvement – Performance-Avoidance Goal – Adaptability	0.000	−0.010	0.011
Total effect	0.451***	0.373	0.521

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

The direct path between parental involvement and adaptability was significant ($\beta = 0.224$, $p < 0.001$). The mediation effect of a mastery goal orientation on the relationship between parental involvement and adaptability was 0.201 ($p < 0.001$), indicating that a mastery goal orientation had a partial positive mediating effect on the correlation between parental involvement and adaptability. The mediation effect of the performance-approach goal orientation between parental involvement and adaptability was 0.027 ($p < 0.01$), indicating that a performance-approach goal orientation had a partial positive mediating effect on the correlation between parental involvement and adaptability. The mediation effect of a performance-avoidance goal orientation between parental involvement and adaptability was not significant ($\beta = 0.000$, $p > 0.05$), indicating that this orientation did not mediate between parental involvement and adaptability. Parental involvement explained 45.1% of the variance of adaptability. Indirect links accounted for 50.6% of the relationship between parental involvement and adaptability, with a stronger link through mastery goals (44.6%) than through performance-approach goals (6.0%).

Discussion

This study applied the integration of the contextual model of parenting and goal theory as the theoretical foundation to examine the relationship between parental involvement, goal orientations, academic buoyancy, and adaptability in maths learning. The results indicated that the students' perceived parental involvement was positively related to their academic buoyancy and adaptability. Furthermore, parental involvement was significantly associated with the students' self-reported mastery and performance-approach goal orientations, which further mediated the relationship between parental involvement and academic buoyancy, as well as the relationship between parental involvement and adaptability. However, the mediating role of a performance-avoidance goal orientation in the relationship was not significant. Our findings provide evidence of the parental and motivational antecedents of academic buoyancy and adaptability in Chinese society and maths learning. The findings and implications are discussed below.

Parental involvement and academic buoyancy and adaptability

The extent of parental involvement perceived by the students positively predicted both academic buoyancy and adaptability. This association indicates that when students perceive greater parental involvement, they are likely to be more competent in dealing with learning difficulties, challenges, uncertainty, and novelty in maths classrooms. These results are consistent with the literature on the influence of parents' behavior on students' mathematical learning abilities (Levine et al., 2010; Ramani et al., 2015), and especially, are in line with the previous findings about the parents' involvement in benefiting students' perceived competence (Fan and Williams, 2010; Núñez et al., 2019). A possible explanation for the contribution of parents' learning-related practices to their children's academic functioning could be found from the perspective of the beliefs held by both parents and children in the Chinese context, shaped by Confucianism and social norms. For Chinese parents, most of them believe that self-improvement is a primary goal of education and they should be responsible for their children's development. Especially, given the critical role of mathematics in preparing youngsters for future employment and personal development (Tan, 2013), they highlight mathematics achievement as being of great importance and are motivated to engage more with their children's maths learning. Influenced by some well-known Chinese sayings, such as "The sharpness of a sword comes from being tempered, and the fragrance of plum blossoms comes from the bitter cold", they consider their children's adaptive responses to complex learning situations as signs that diligence is developing. When children come across difficulties or any situations never encountered before in maths learning, parents are willing to provide behavior and emotional support, which benefits the development of children's academic buoyancy and adaptability. For Chinese students, the ideas that academic success can bring honor to the whole family and is a demonstration of filial piety (Ng and Wang, 2019) and their perceptions of the value their parents place on effort and persistence, may strengthen the process of internalization needed to cope with challenges, difficulties, novelty, and uncertainty in the maths learning process. This then means that they are more competent academically and prioritize both effort and academic outcomes.

Parental involvement and goal orientations

This research identified positive correlations between parental involvement and two goal orientations (mastery and performance-approach goal orientations), in line with the literature (e.g., Gonzalez and Wolters, 2006; Duchesne and Ratelle, 2010; Zong et al., 2018). As discussed above, high expectations of academic achievement and parents' responsibility for training their children are promoted in Chinese society, based on Confucianism. The beneficial effect of parental practices on students' motivation to achieve may be the result of students seeing their parents taking a great interest in their education and getting actively involved in their maths learning. The children get the message that their parents are committed to the young person's academic ability and success, and may conclude that growth and self-improvement are their primary responsibility. This autonomy fosters the development of students' mastery orientation. Meanwhile, greater parental involvement may elicit students' mindset that they need to excel academically and outperform peers, strengthening their performance-approach goal orientation (Gonzalez and Wolters, 2006).

Contrary to our hypothesis, there was no significant correlation observed between parental involvement and performance-avoidance goal orientation, but it is consistent with the findings of Zong et al. (2018). This finding suggests that the effect of the avoidance-oriented motivation provided by parental involvement may dissipate when learning maths. This pattern may be due to China's newly released compulsory education policy. This is called "the double reduction policy" and it aims to ease the learning burden and examination pressure on students by adjusting homework assignments, reducing the importance of test scores, and prohibiting after-school tutoring. Improving maths skills to support students' future learning and career development is a major pillar of the current reform of mathematics education in China. As a result, regardless of the extent of parental involvement, excessive concerns about demonstrating poor academic competence and failure in education have generally declined among Chinese junior high school students. Their avoidance tendency may have become independent of parental intervention.

The mediating roles of goal orientations

The path analysis showed that the mastery goal and performance-approach goal orientations significantly and partially mediated the relationship between parental involvement and academic buoyancy, as well as adaptability (i.e., greater parental involvement is indirectly linked to higher academic buoyancy and adaptability by fostering both mastery and performance-approach goal orientations). The mediating role of the two goal orientations found in this study is partially consistent with the contextual model of parenting and goal theory discussed above. Parental behaviors can influence learners' learning motivation (Darling and Steinberg, 1993). When parents get involved in their children's maths learning, they may provide encouragement and praise for good mathematics performance, show that they have high expectations, and highlight the importance of self-improvement. These behaviors may create a cognitive and psychological environment in which students understand that they need to develop and prove their ability and realize the importance of academic success. Then, these goal orientations may be beneficial for students to trigger adaptive coping motivation when dealing with complex problems in learning (Kaplan and Maehr, 2007). To be specific, students who endorse the goals of developing and demonstrating competence and pursuing academic success may also show task persistence, preference for challenges, and ease with uncertainty. However, the performance-avoidance goal orientation did not mediate the relationship, which is inconsistent with the findings of previous studies regarding its mediating effect on the relations between parental behaviors and students' academic functioning (e.g., Chen, 2015; Xiang et al., 2017; Xu et al., 2018). This may be because parental involvement in mathematics learning helps students develop their perceived control over their abilities. In challenging or changing situations, students who benefit from sufficient parental involvement in their education may believe that only adaptive and positive adjustments in response to those situations will assist them in attaining academic success. A performance-avoidance goal orientation does not need to be psychologically prominent for these adjustments to occur. The function of performance-avoidance goals should be explored further in the future.

Limitations and future research directions

Despite its significant findings, the study has a few limitations that should be acknowledged. First, the information about the relevant variables was self-reported by the participants in response to a questionnaire. Although it is assumed that self-reported data reflect participants' actual thoughts and behavior, participants' responses may sometimes be inconsistent with their actions. Future studies should adopt various assessments, such as observations or interviews to triangulate the data. Second, this research measured parental involvement by adopting a unidimensional scale. Considering multiple aspects of parental involvement may have different effects on students' mathematics learning, future research can use the multidimensional measurement of parental involvement and avoid broadly defining this concept. Third, this study used a cross-sectional design to test the research hypotheses. Although the method is efficient and accurate, it is impossible to explore the correlations over time and understand the causality between the variables. Future work should use longitudinal investigations to test the causal associations. Fourth, only 8th-grade students and their parents/guardians were recruited for this research; care should be taken in extending the results to individuals in different school years. As for directions for future work, studies should recruit more representative and diverse samples.

Implications and conclusions

Our findings suggest that the degree of parents' involvement in mathematics learning and students' beliefs about the reasons for achieving success can act as protective factors for students when faced with academic difficulties, challenges, and new situations of any kind. It is important to encourage parents to spend more time providing effective support for their children's maths learning activities. Schools should increase opportunities to boost parental involvement by organizing training activities and communications with parents about students' progress. Teachers could launch public workshops to offer tips to help with mastering maths, coping strategies for learning challenges, and, most importantly, what parents can do to cultivate their children's maths learning abilities. In addition, educators could seek to motivate students to trigger their psychological autonomy and develop healthy goal orientations.

In conclusion, this is the first study to examine both the family and individual antecedents of academic buoyancy and adaptability in the maths learning field. It supports our conjecture about the unique roles of mastery and performance-approach goal orientations as mediators of the relationship between parental involvement and academic buoyancy and adaptability. The findings hint at the potential roles played by culture and social context and also contribute to a more complete portrait of parental impact on students' proficiency in learning and the motivational process behind it. We hope that our findings will provide a useful foundation for future studies of the development of students' academic buoyancy and adaptability.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by the University of Hong Kong's Human Research Ethics Committee (HREC). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

MC conducted the survey, analyzed the data, and wrote the manuscript. IM supervised the investigating, analyzing, and writing process. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The neuroscience basis and educational interventions of mathematical cognitive impairment and anxiety: a systematic literature review

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Introduction: Mathematics is a fundamental subject with significant implications in education and neuroscience. Understanding the cognitive processes underlying mathematical cognition is crucial for enhancing educational practices. However, mathematical cognitive impairment and anxiety significantly hinder learning and application in this field. This systematic literature review aims to investigate the neuroscience basis and effective educational interventions for these challenges.

Methods: The review involved a comprehensive screening of 62 research articles that meet the ESSA evidence levels from multiple databases. The selection criteria focused on studies employing various methodologies, including behavioral experiments and neuroimaging techniques, to explore the neuroscience underpinnings and educational interventions related to mathematical cognitive impairment and anxiety.

Results: The review identified key themes and insights into the neuroscience basis of mathematical cognitive impairment and anxiety. It also examined their impact on educational practices, highlighting the interplay between cognitive processes and educational outcomes. The analysis of these studies revealed significant findings on how these impairments and anxieties manifest and can be addressed in educational settings.

Discussion: The review critically analyzes the shortcomings of existing research, noting gaps and limitations in current understanding and methodologies. It emphasizes the need for more comprehensive and diverse studies to better understand these phenomena. The discussion also suggests new directions and potential improvement strategies for future research, aiming to contribute to more effective educational interventions and enhanced learning experiences in mathematics.

Conclusion: This systematic review provides valuable insights into the neuroscience basis of mathematical cognitive impairment and anxiety, offering a foundation for developing more effective educational strategies. It underscores the importance of continued research in this area to improve educational outcomes and support learners facing these challenges.

KEYWORDS

mathematical cognitive impairment, mathematical anxiety, neuroscience, educational interventions, systematic literature review

1 Introduction

Mathematics, as a universal and foundational subject, has extensive applications in various fields such as society, technology, and economics. Particularly in education and neuroscience, the study of mathematical cognition has gradually become an important research object (Sotiropoulos, 2014). This involves complex issues of how humans acquire, process, and apply mathematical knowledge (Moustafa et al., 2017). In education, exploring the processes and mechanisms of mathematical cognition helps optimize teaching methods, improve students' learning processes, and enhance overall teaching effectiveness (Gilmore, 2023; Medrano and Prather, 2023). Simultaneously, in neuroscience, studying the neural basis of mathematical cognition allows us to understand the operating mechanisms of the brain more deeply (Matejko and Ansari, 2015; Looi et al., 2016). However, in the research and application of mathematical cognition, mathematical cognitive impairment and mathematical anxiety are two universal and severe problems (Moustafa et al., 2019). Mathematical cognitive impairment often leads to persistent difficulties in mathematical learning and application, severely affecting academic achievements and potentially negatively impacting future career development and social adaptability. Mathematical anxiety typically manifests as tension and anxiety when individuals face mathematical tasks, likely exacerbating the problems of mathematical cognitive impairment (Henschel and Roick, 2020). To explore the causes, manifestations, and intervention methods of these two problems, researchers have conducted extensive research using various methods such as behavioral experiments and neuroimaging, achieving some research results. However, there are still many unresolved issues and deficiencies regarding the neuroscience basis of mathematical cognitive impairment and anxiety and how to effectively alleviate these two problems through educational interventions.

This paper aims to explore and analyze the neuroscience basis of mathematical cognitive impairment and anxiety and how these bases affect the methods and effects of educational practices by reviewing related literature. It will focus on exploring the neural level performance characteristics of mathematical cognitive impairment and anxiety, their mutual influences, and effective ways to alleviate these problems through educational interventions. It will also summarize and analyze the shortcomings of existing research, aiming to find new directions and possible improvement strategies for future research. We hope this paper can provide valuable references and inspirations for the theory and practice of mathematical education.

2 Methods

The objective of this systematic literature review is to construct an understanding of mathematical anxiety and cognitive impairment from the existing research foundation, aiming to identify significant themes within the current knowledge base. Our review process included formulating research questions; determining the scope of search terms; selecting databases; establishing reasonable inclusion and exclusion criteria; evaluating evidence levels; expanding database search results; identifying meaningful outcomes, patterns, and trends; and conveying contributions(see Figure 1).

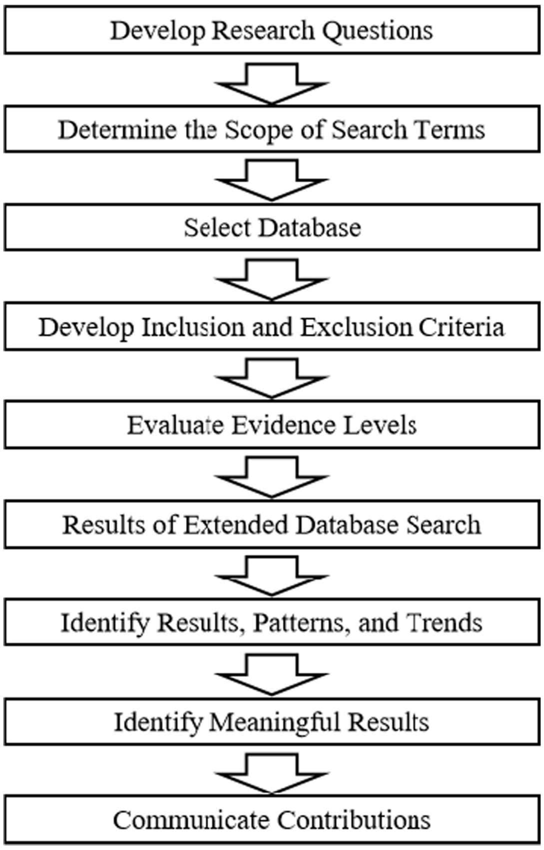

FIGURE 1
Systematic literature review process.

For this study, we utilized several search engines: Web of Science, EBSCO, Scopus, and ERIC. These engines were chosen based on their breadth and tendency to be more comprehensive than other databases. The initial primary search terms used were "mathematics," "math education," "mathematical," and "math cognition," each paired with "neuroscience," "anxiety," and "cognitive impairment." We did not use a specific year range for the search, opting instead for an open search to observe a more comprehensive representation. The preliminary search yielded 2,328 articles. From the results, 419 duplicate articles were removed. Our systematic literature review included a snowball sampling strategy, identifying additional studies by reviewing citations from articles in our preliminary search, incorporating an additional 29 articles, totaling 1938. The screening process involved two rounds of review, applying our search inclusion and exclusion criteria to narrow down the pool of articles suitable for inclusion. The first round of screening primarily focused on the titles and abstracts of the articles, excluding 1,526 articles, leaving 369. Table 1 provides examples of the excluded articles.

The second round of screening involved using the ESSA evidence levels to assess the eligibility of full-text articles, determining which articles should be included in the review based on the rigor of the research (see Figure 2) (Thomas and Harden, 2008). 307 articles were excluded as they did not meet the ESSA evidence levels. The final 62 articles included: 7 meeting ESSA Tier 1, 9 meeting ESSA Tier 2, 15 meeting ESSA Tier 3, and 31 meeting ESSA Tier 4.

TABLE 1 Sample of excluded articles.

Sample of excluded articles	
Non mathematical neuroscience	
1	Abbott, L. F. (2008). Theoretical neuroscience rising. Neuron, 60(3), 489–495.
2	Silva, A. C., Tomassini, C., Zurbrigg, J., Palacios, A., Amarante, V., & Bouzat, C. (2021). Gender inequality in Latin American Neuroscience community. IBRO Neuroscience Reports, 10, 104–108.
3	Sizemore, A. E., Phillips-Cremins, J. E., Ghrist, R., & Bassett, D. S. (2019). The importance of the whole: Topological data analysis for the network neuroscientist. Network Neuroscience, 3(3), 656–673.
4	Baker, D. P., Salinas, D., & Eslinger, P. J. (2012). An envisioned bridge: Schooling as a neurocognitive developmental institution. Developmental Cognitive Neuroscience, 2, S6–S17.
5	Silver, R., Boahen, K., Grillner, S., Kopell, N., & Olsen, K. L. (2007). Neurotech for neuroscience: unifying concepts, organizing principles, and emerging tools. The Journal of Neuroscience, 27(44), 11,807–11,819.
…	
Not paying attention to mathematics education	
1	McCollum, G. (2003). Mathematics reflecting sensorimotor organization. Biological Cybernetics, 88(2), 108–128.
2	Gutkin, B., Pinto, D., & Ermentrout, B. (2003). Mathematical neuroscience: from neurons to circuits to systems. Journal of Physiology-paris, 97(2–3), 209–219.
3	Amigó, J. M., & Small, M. (2017). Mathematical methods in medicine: neuroscience, cardiology and pathology. Philosophical Transactions of the Royal Society A, 375(2096), 20,170,016.
4	Tallant, J. (2013). Pretense, Mathematics, and Cognitive Neuroscience. The British Journal for the Philosophy of Science, 64(4), 817–835.
5	Feng, S. F., & Holmes, P. (2016). Will big data yield new mathematics? An evolving synergy with neuroscience. Ima Journal of Applied Mathematics, 81(3), 432–456.
…	
Not paying attention to mathematical cognitive impairment and mathematical anxiety	
1	Van Nes, F. (2011). Mathematics Education and Neurosciences: Towards interdisciplinary insights into the development of young children's mathematical abilities. Educational Philosophy and Theory, 43(1), 75–80.
2	Ng, S. S. N., & Rao, N. (2010). Chinese number words, culture, and mathematics learning. Review of Educational Research, 80(2), 180–206.
3	Anderson, O. R., Love, B. C., & Tsai, M. J. (2014). Neuroscience Perspectives for science and Mathematics Learning in Technology-Enhanced Learning Environments. International Journal of Science and Mathematics Education, 12(3), 467–474.
4	Cuturi, L. F., Cappagli, G., Yiannoutsou, N., Price, S., & Gori, M. (2021). Informing the design of a multisensory learning environment for elementary mathematics learning. Journal on Multimodal User Interfaces, 16(2), 155–171.
5	Wilkey, E. D., Cutting, L. E., & Price, G. R. (2017). Neuroanatomical correlates of performance in a state-wide test of math achievement. Developmental Science, 21(2).
…	

We employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, an evidence-based standard for systematic reviews and meta-analyses, to guide the selection and analysis of literature methods. Figure 3 displays a PRISMA flow diagram summarizing the process used to identify studies.An information database was constructed using the articles included in the systematic literature review. The database comprised general information (e.g., article titles, authors, publication dates, publications, and abstracts), research types (e.g., research questions, methods), and summaries of findings. The authors used the PRISMA guidelines to elucidate the data collection and analysis methods for each study.

We did not use a conceptual framework to construct the coding process but employed thematic synthesis to analyze the articles, where themes were generated from the primary studies. The three stages of this method were: (1) coding selected texts, (2) developing descriptive themes, and (3) generating analytical themes. For each article, findings, discussions, and implications were independently coded by the authors of this manuscript and then discussed collectively. Emergent codes were identified, descriptive themes developed, and analytical themes generated. After a rigorous screening process and analysis, we selected a series of primary literatures on mathematical anxiety and cognitive impairment. These literatures mainly fall into several categories (see Table 2).

Through the comprehensive analysis and summary of these literatures, we can gain a deeper understanding of the neuroscience basis of mathematical anxiety and cognitive impairment and how to apply this knowledge in educational practices. This not only helps us understand the nature of mathematical anxiety and cognitive impairment more comprehensively but also assists us in finding more effective assessment and intervention methods.

3 Results

This review aims to explore the neural foundations of mathematical cognition, mathematical cognitive impairment, and math anxiety, as well as the implications of neuroscience research findings for math education.

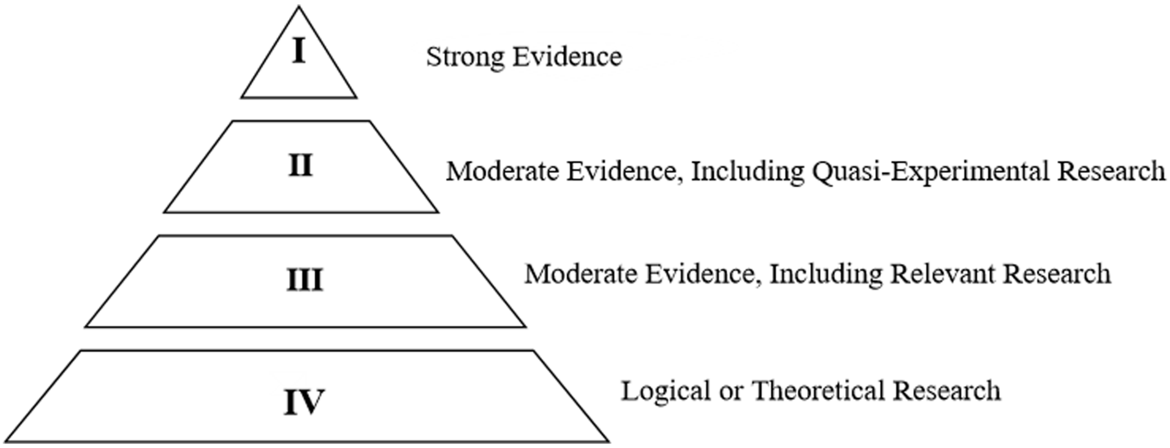

FIGURE 2
ESSA Evidence Hierarchy.

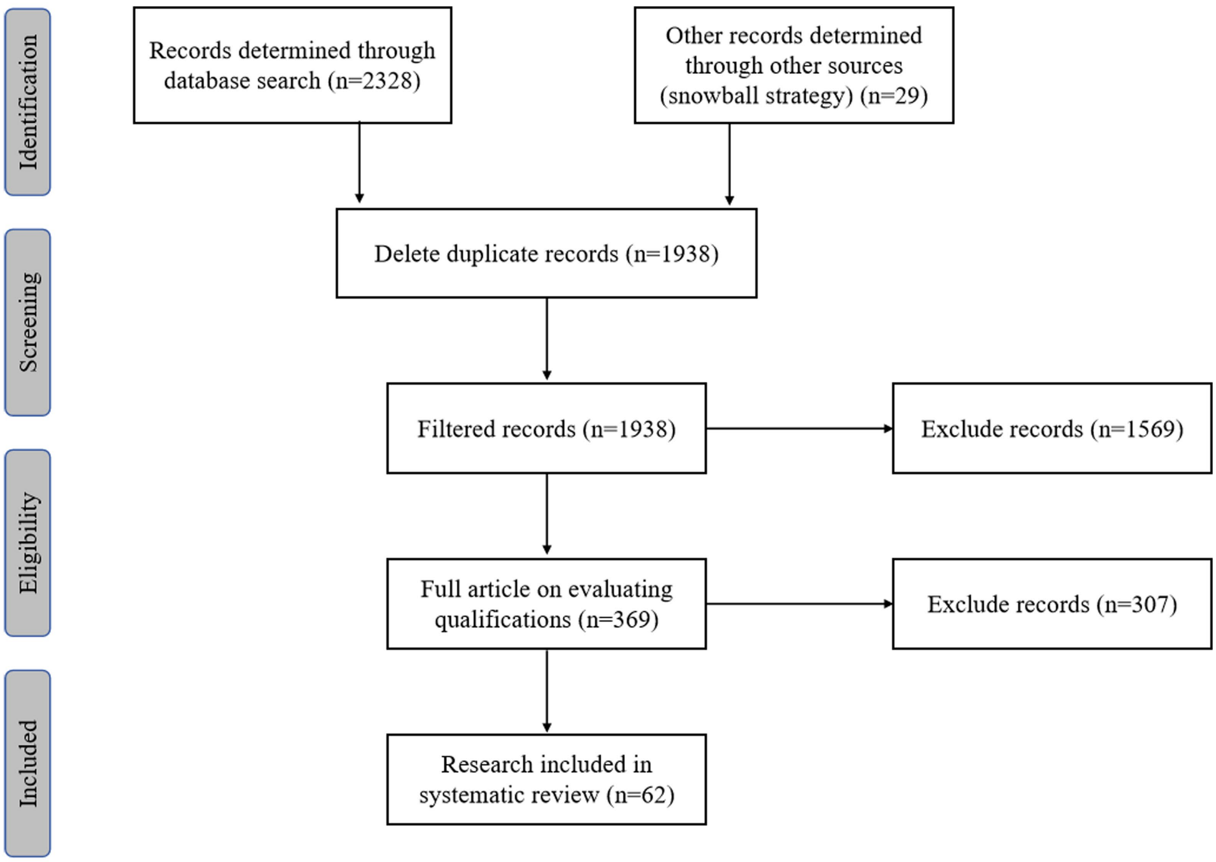

FIGURE 3
Preferred reporting items for PRISMA diagram of selection process.

3.1 Neural foundations of mathematical cognition

Mathematical cognition, as a complex psychological process, involves activities in multiple brain regions. While studies have indicated associations between different components of mathematical cognition and specific brain regions, it's crucial to note that these relationships are not always straightforward or one-to-one. For instance, while number representation and processing, arithmetic rules and calculations, and problem-solving have been linked to

TABLE 2 Main classification of literature.

Theme	Content	Number of documents	Quantity proportion
Relationship Between Mathematical Anxiety and Cognitive Function	Focuses on how mathematical anxiety impacts individual cognitive functions such as working memory, attention, and executive functions.	37	59.7%
Assessment and Intervention for Mathematical Anxiety	Investigates the assessment and intervention strategies for mathematical anxiety, including various assessment tools and intervention approaches.	25	40.3%
Diagnosis and Characteristics of Mathematical Learning Disabilities	Explores the diagnostic criteria, characteristics, and classification of mathematical learning disabilities.	18	29.0%
Neurobiological Basis of Mathematical Learning Disabilities	Addresses the neurobiological basis of mathematical learning disabilities, including abnormalities in brain structure and function.	26	41.9%
Intervention and Educational Strategies for Mathematical Learning Disabilities	Explores how different educational and psychological intervention strategies can assist individuals with mathematical learning disabilities.	39	62.9%
Relationship Between Mathematical Anxiety and Cognitive Function	Focuses on how mathematical anxiety impacts individual cognitive functions such as working memory, attention, and executive functions.	13	21.0%

distinct cognitive mechanisms and brain activities (Newman et al., 2011; Bulthé et al., 2014; Park et al., 2014), Cappelletti et al. (2012) found that most patients with focal brain lesions exhibited calculation deficits but did not necessarily show deficits in nonsymbolic quantity recognition. This was observed both in patients with parietal lesions and those with lesions in other brain areas, suggesting a more intricate relationship between brain regions and numerical cognition than previously assumed.

3.2 Mathematical cognitive impairment

Mathematical cognitive impairment is a complex phenomenon, covering two main areas: developmental calculation disorders and acquired calculation disorders. Developmental calculation disorders typically manifest during the natural developmental process of children, appearing as difficulties in number and calculation abilities without evident neural system damage or specific brain region developmental delays (Lu et al., 2020). These difficulties extend beyond mathematical calculations, including number recognition, comparison, and estimation, possibly due to fundamental neurobiological defects such as working memory, attention, and executive function deficits (Li et al., 2013; Bulthé et al., 2019; Klados et al., 2019). Acquired calculation disorders, on the other hand, result from external factors like brain injuries or diseases, leading to the loss or decline of previously acquired mathematical abilities (Siemann and Petermann, 2018), typically emerging in adulthood and potentially affecting individuals' daily lives and career development.

3.3 Math anxiety

Math anxiety refers to the tension and unease experienced by individuals when facing mathematical tasks. This anxiety can negatively impact the completion of mathematical tasks, such as reducing task accuracy and efficiency (Foley et al., 2017). Math anxiety may be related to individuals' self-evaluation, math self-efficacy, and past math experiences. Research has found that math anxiety is associated with activities in specific brain regions, such as the amygdala (Atabek et al., 2022). Individuals with high math anxiety show excessive activity in the amygdala region of the brain when facing mathematical tasks, indicating that math anxiety is not only a psychological phenomenon but also related to brain physiological activities. Math anxiety affects mathematical cognition, including number representation, calculation, and problem-solving (Suárez-Pellicioni et al., 2013; Peña and Suárez-Pellicioni, 2014; Klados et al., 2015). For instance, math anxiety might interfere with individuals' working memory, making them more likely to feel confused and lose focus when solving mathematical problems. Additionally, math anxiety may also affect individuals' math learning and long-term math achievements (Peña et al., 2019).

3.4 Interaction between math anxiety and cognitive impairment

There is a close interaction between math anxiety and cognitive impairment. Math anxiety might exacerbate the manifestations of cognitive impairment and vice versa (Devine et al., 2018). For example, math anxiety might affect individuals' attention allocation and information processing strategies, thereby affecting their mathematical cognition performance (Pizzie and Kraemer, 2017). At the same time, individuals with cognitive impairments might develop higher math anxiety due to their mathematical ability deficiencies (Young et al., 2012).

3.5 Implications of neuroscience research findings for math education

The findings from neuroscience provide new perspectives and theoretical support for math education. For instance, educators can design teaching strategies more aligned with students' cognitive development based on the neural foundations of mathematical cognition (Tschentscher and Hauk, 2014). Moreover, for mathematical cognitive impairment and math anxiety, educators can formulate more scientific and effective teaching and intervention strategies based on neuroscience research findings (Faramarzi and Sadri, 2014).

In conclusion, math anxiety and cognitive impairment play significant roles in mathematical cognition. Understanding their neural foundations and mechanisms of mutual influence is crucial for optimizing math education strategies and improving teaching outcomes. In the subsequent discussion section, we will explore issues related to mathematical cognitive impairment and math anxiety more deeply, aiming to provide more comprehensive and profound theoretical support for the improvement and development of math education.

4 Discussion

4.1 Neural mechanisms of math anxiety

Math anxiety, as a significant research subject in psychology and education fields, has its neurobiological foundations becoming a current research hotspot. Through neuroimaging technologies such as functional magnetic resonance imaging (fMRI), researchers aim to unveil the neural mechanisms and network connections behind math anxiety (Newman et al., 2011). Firstly, from an emotional processing perspective, studies have found that individuals with math anxiety, when facing mathematical tasks, show more active neural activities in brain regions related to emotional processing, such as the amygdala (Atabek et al., 2022). The amygdala, as a core area for emotional responses and processing, indicates that math anxiety is closely related to the brain's emotional regulation mechanisms (Atabek et al., 2022). This connection might be a crucial neural foundation for the emergence and maintenance of math anxiety. Secondly, math anxiety is also related to the brain's cognitive control areas. Research indicates that in individuals with math anxiety, brain regions related to executive functions and attention regulation, such as the prefrontal and parietal lobes, might display activity patterns different from those of normal individuals when processing mathematical tasks (Chen et al., 2006). These differences might lead to issues in cognitive resource allocation and utilization in individuals with math anxiety, thereby affecting task completion efficiency and accuracy. Additionally, math anxiety might also be related to the brain's default mode network (DMN). Some studies have found that the DMN's activity might be affected in individuals with math anxiety during mathematical tasks (Pletzer et al., 2015). The DMN is usually active when individuals are at rest and decreases in activity during specific cognitive tasks (Gotlieb et al., 2016). Math anxiety might affect this network's normal functions, thereby affecting individuals' cognitive performance. In conclusion, the neural mechanisms of math anxiety might involve multiple brain regions and networks, including those related to emotional processing, cognitive control, and the default mode network (Young et al., 2012; Pletzer et al., 2015; Meijer et al., 2022). This multi-region, multi-network involvement suggests that math anxiety is a complex psychological phenomenon, influenced by various neural factors. A deeper understanding of the neural mechanisms of math anxiety can not only help us comprehend this phenomenon more comprehensively and accurately but also provide more scientific and effective theoretical guidance for clinical interventions and educational practices. For instance, targeted regulation and training of related brain regions and networks might help alleviate the degree of math anxiety, improving individuals' math learning and performance (Liu et al., 2019). This will contribute to the advancement of math education, enhancing the quality and effectiveness of education.

4.2 Relationship between mathematical anxiety and components of mathematical cognition

Math anxiety is a specialized, negative emotional reaction directed towards math learning and evaluation. This emotional reaction is not merely limited to superficial emotional experiences; more profoundly, it is intricately linked to the cognitive components of math—such as number representation, calculation, and problem-solving (Suárez-Pellicioni et al., 2013; Peña and Suárez-Pellicioni, 2014; Klados et al., 2015). Through in-depth analysis and exploration, we can more comprehensively understand how math anxiety permeates and influences an individual's mathematical cognitive processes.

Firstly, we explore the relationship between math anxiety and number representation. Number representation is foundational to mathematical cognition, involving the cognitive representation of numbers and quantities (Bulthé et al., 2014). Individuals with high math anxiety may encounter difficulties in number representation (Piazza and Eger, 2016). For instance, when engaging in tasks such as number magnitude comparison, number ordering, and number line positioning, they may not perform as well as those with low math anxiety. This could be because the excessive attention and worry triggered by math anxiety interfere with the normal processing and encoding of numerical information, affecting the process of number representation (Kanayet et al., 2018).

Secondly, we examine how math anxiety impacts calculation abilities. Calculation abilities are a core component of mathematical cognition, encompassing basic arithmetic calculations and complex mathematical operations (Yi-Rong et al., 2011; Van Der Ven et al., 2016). Research has found that individuals with high math anxiety may make more errors and take longer reaction times when performing arithmetic calculations (Kanayet et al., 2018). This might be due to math anxiety consuming substantial cognitive resources, such as attention and working memory, preventing individuals from fully concentrating when processing calculation tasks, thereby affecting the accuracy and efficiency of calculations.

Lastly, we investigate the relationship between math anxiety and problem-solving abilities. Problem-solving is an advanced process in mathematical cognition, involving metacognitive skills such as strategy selection, planning, and self-monitoring. Individuals with high math anxiety, when facing mathematical problems, may feel more anxious and uneasy, which could affect their strategy selection and problem-solving processes. For example, they might exhibit more hesitation and uncertainty during problem-solving, and the strategies they choose may not be as effective and reasonable (Peters et al., 2016).

By deeply exploring the relationship between math anxiety and components of mathematical cognition, we can see how math anxiety influences mathematical cognition through various pathways and mechanisms. Math anxiety might indirectly affect the execution of mathematical tasks by occupying limited cognitive resources and disrupting the normal functioning of attention and working memory (Evans et al., 2016). Simultaneously, math anxiety might also directly interfere with the problem-solving process by affecting individuals' metacognitive skills, such as self-monitoring and strategy selection (Peters et al., 2016).

In conclusion, there exists a complex and multi-layered interaction and influence between math anxiety and the components of mathematical cognition. To more effectively understand and alleviate the negative impacts of math anxiety, future research could further delve into the specific mechanisms and pathways of these interactions, providing more scientific and targeted guidance and recommendations for educational practice.

4.3 Manifestations and characteristics of cognitive impairments

In discussing cognitive impairments in mathematical cognition, literature primarily focuses on Developmental Calculation Disorder (DCD) and Acquired Calculation Disorder (ACD) (Kucian et al., 2013; Van Beek et al., 2015). Both types of impairments are mainly characterized by deficiencies in numerical and calculation abilities, but their manifestations and etiologies differ.

4.3.1 Developmental calculation disorder (DCD)

DCD, as a specific learning impairment, predominantly manifests during the mathematical learning process in children. This impairment is usually persistent, affecting individuals' performance in various areas such as numerical processing, basic arithmetic skills, and mathematical problem-solving (Kaufmann et al., 2011; Kucian et al., 2011; Kucian and Von Aster, 2014). Notably, studies like Demeyere et al. (2010) and Demeyere et al. (2012) have highlighted dissociations between components like subitizing and counting in patients with dyscalculia. Furthermore, the work of Brian Butterworth has extensively delved into the intricacies of mathematical cognition and its disorders. While DCD is often associated with unusual patterns of brain functioning, particularly involving the parietal lobes, it is rarely the result of brain damage and is unlikely to have an exact parallel with acquired dyscalculia (ACD). There is still controversy about the exact nature and causes of DCD (Murphy et al., 2007; Kaufmann et al., 2013; Träff et al., 2017). A detailed exploration and analysis of DCD manifestations, based on literature, will be conducted (see Table 3) (Van Harskamp and Cipolotti, 2001; Kaufmann et al., 2011; Kucian et al., 2011; Faramarzi and Sadri, 2014; Kucian and Von Aster, 2014).

TABLE 3 Manifestations of developmental dyscalculia.

Domain	Subdomain	Difficulties experienced by children with DCD
Numerical Processing	Number Recognition	More time needed for number recognition, errors may occur during the process
	Numerical Magnitude Representation	Difficulties in accurately comparing and estimating numbers, challenges in number sorting and categorization
Basic Arithmetic Skills	Arithmetic Rules and Strategies	Deficiencies in mastering and applying basic arithmetic rules and strategies
	Calculation Efficiency	Reliance on finger and physical counting, lack of effective calculation strategies and techniques
Problem-Solving Ability	Problem-Solving Strategies	Lack of effective and flexible problem-solving strategies
	Efficiency and Accuracy in Problem-Solving	Lower efficiency, higher error rates, confusion, and frustration when facing complex and novel problems

Through an in-depth analysis of DCD children in terms of numerical processing, basic arithmetic skills, and mathematical problem-solving abilities, we can more comprehensively and accurately understand the mathematical learning characteristics and difficulties of this group. This is crucial for educators and mental health professionals to provide more precise and personalized support during diagnosis and intervention. Moreover, it helps further explore and understand the causes and mechanisms of mathematical learning impairments, providing a richer and more profound theoretical foundation for future research and practice.

4.3.2 Acquired calculation disorder (ACD)

ACD, as a unique form of mathematical cognitive impairment, is typically due to brain injury or neurological disorders (Siemann and Petermann, 2018). Unlike DCD, individuals with ACD might have successfully acquired certain mathematical skills earlier, but due to subsequent factors such as brain injury or disease, these skills may be lost or deteriorated (Miundy et al., 2019). The main manifestations and characteristics of ACD, such as loss of mathematical skills, calculation difficulties, and mathematical thinking impairments, will be deeply explored.

Loss of Mathematical Skills:Individuals with ACD may lose some basic mathematical skills that they had previously mastered, including basic arithmetic abilities, understanding, and application of mathematical concepts (González et al., 2019). They might find simple arithmetic operations challenging or feel confused when understanding and applying basic mathematical concepts and formulas. This loss may affect their mathematical application abilities in daily life and learning, such as calculating shopping expenses and measuring object lengths and areas (Benavides-Varela et al., 2017).

Calculation Difficulties:Due to brain injuries, individuals with ACD may face significant challenges in mathematical calculations (Cohen et al., 2018). This includes not only complex mathematical calculations, such as solving algebraic and geometric problems, but also simpler tasks like basic arithmetic operations (Kaufmann, 2008; Kunwar, 2021). They might make mistakes easily during calculations or take longer to complete tasks that should be simple and quick.

Mathematical Thinking Impairments:Individuals with ACD may also have certain limitations in mathematical thinking and reasoning (Siemann and Petermann, 2018). They might display rigidity, lack of creativity, and flexibility when facing mathematical problems (Claros-Salinas et al., 2014; Hobri et al., 2021). They might find it difficult to understand and master new mathematical concepts and methods or lack effective problem-solving strategies and methods. Additionally, they might struggle with abstract thinking and logical reasoning, such as understanding and applying abstract mathematical concepts and theorems.

In conclusion, ACD, as a special form of mathematical cognitive impairment, is mainly characterized by the loss of mathematical skills, calculation difficulties, and mathematical thinking impairments. These impairments may severely affect the mathematical application abilities and performance of individuals with ACD in learning, work, and daily life (Kaufmann et al., 2013). Therefore, more attention and support are needed for individuals with ACD, helping them overcome obstacles and improve mathematical cognition and application abilities through effective educational and rehabilitative interventions.

By analyzing developmental and acquired calculation disorders, it is evident that although both are related to deficiencies in mathematical cognitive abilities, their causes, manifestations, and impacts are distinct. Understanding and distinguishing the characteristics of these impairments are essential for better understanding the potential issues in mathematical cognitive processes and providing more precise and effective assistance to individuals facing difficulties.

4.4 Neural basis of cognitive impairments

In the profound exploration of cognitive impairments, scholars have utilized sophisticated neuroimaging technologies such as Diffusion Tensor Imaging (DTI), conducting a series of exhaustive investigations into the neural foundations of cognitive impairments (Kucian et al., 2013). These explorations aim to unveil the neural structural and functional abnormalities underlying the difficulties encountered by individuals with cognitive impairments during mathematical tasks (Murphy et al., 2007).

Initially, research has revealed that individuals with cognitive impairments may exhibit structural and functional anomalies in critical brain regions such as the parietal and frontal lobes (Kaufmann et al., 2011; Bulthé et al., 2019). These lobes, essential components of the brain, play central roles in cognitive processes such as spatial representation, attention, memory, and executive functions (Kaufmann et al., 2011). In the parietal lobe, abnormalities may be related to difficulties in spatial representation and visual–spatial processing, crucial for understanding and solving geometric and spatially related mathematical problems (Bulthé et al., 2019). In the frontal lobe, anomalies might predominantly affect executive functions, including planning, organization, and self-monitoring, essential elements in mathematical problem-solving (Kaufmann et al., 2011).

Furthermore, utilizing neuroimaging technologies like DTI, researchers have discovered potential abnormalities in the white matter pathways of individuals with cognitive impairments (Jolles et al., 2015). White matter pathways, the "highways" for neural information transmission between various brain regions, are vital for ensuring coordination and integration among different functional networks of the brain (Kucian et al., 2013). In individuals with cognitive impairments, abnormalities in these pathways might lead to reduced efficiency in information transmission, thereby affecting the processing and integration of mathematical information. Additionally, these neural foundation abnormalities might be directly linked to the specific manifestations of individuals with cognitive impairments in mathematical tasks (Davidse et al., 2014). For instance, anomalies in the parietal and frontal lobes might make it challenging for individuals to effectively organize and utilize relevant strategies and knowledge during mathematical calculations and problem-solving. Abnormalities in the white matter pathways might affect the mobilization and utilization of various cognitive resources when handling complex mathematical tasks (Grant et al., 2020).

These research findings offer invaluable perspectives, aiding in a more comprehensive and profound understanding of the neural mechanisms of cognitive impairments in mathematical learning. This not only facilitates the enhancement of precision in the diagnosis and assessment of cognitive impairments but also provides robust theoretical support for devising effective educational intervention measures and strategies. A deeper understanding of the neural basis of cognitive impairments allows for the development of more targeted teaching methods and strategies that align with the characteristics of individuals with cognitive impairments, aiming to better support their development and progress in mathematical learning.

4.5 Research on intervention strategies

In exploring intervention strategies for mathematical anxiety and cognitive impairments, researchers have employed various methods, aiming to find effective ways to alleviate individuals' mathematical anxiety and improve their mathematical cognitive abilities.

4.5.1 Cognitive training interventions

Recently, cognitive training has emerged as a crucial intervention strategy, extensively researched and applied to alleviate mathematical anxiety and improve cognitive impairments. To enhance individuals' cognitive abilities and information processing efficiency in mathematical learning, researchers have meticulously designed a series of systematic cognitive tasks. Among them, working memory training is a core component of cognitive training, involving the cognitive system where people temporarily store and manipulate information, directly affecting mathematical learning outcomes (De Vreeze-Westgeest and Vogelaar, 2022). Researchers, through designing tasks of various forms and difficulties such as n-back tasks and complex span tasks, intentionally enhance individuals' working memory capabilities (Schmidt et al., 2009; Lucidi et al., 2014). With continuous and regular training, individuals can process and manipulate information more effectively in mathematical tasks, reducing the cognitive load caused by mathematical anxiety.

Cognitive training also includes attention control training, helping individuals selectively focus on and process task-related information while ignoring irrelevant distractions (Bishara and Kaplan, 2021). Through specialized training such as the Flanker task and Stroop task, individuals learn to concentrate better, reducing attention dispersion and cognitive resource consumption caused by anxiety (Van Der Ven et al., 2011; Van Nes, 2011; Peralbo et al., 2020). Additionally, cognitive training emphasizes enhancing other cognitive functions such as executive functions and spatial abilities (Wu et al., 2019; Chatzivasileiou and Drigas, 2022). These trainings assist individuals in more flexibly and accurately applying various strategies and methods during the mathematical learning process, improving problem-solving abilities. During the implementation of cognitive training, researchers particularly emphasize the individualization and adaptability of training, adjusting the difficulty and content of training tasks timely based on each individual's baseline abilities and progress, ensuring the effectiveness and efficiency of the training (Chipman, 2010).

In conclusion, cognitive training, as an intervention strategy based on cognitive psychology principles, shows immense potential in alleviating mathematical anxiety and improving cognitive impairments by specifically training cognitive functions such as working memory and attention control. Looking forward, research can further explore the optimal implementation methods and effectiveness evaluation approaches of cognitive training, providing more scientific and effective guidance and strategies for cognitive training-based interventions.

4.5.2 Application of psychological interventions

The significance of psychological interventions in alleviating mathematical anxiety has been widely affirmed by extensive research. As an effective strategy to mitigate mathematical anxiety, psychological interventions not only assist individuals in altering their thought processes and emotional responses, thereby reducing the levels of mathematical anxiety, but also enhance individuals' confidence and efficiency in mathematical learning. Cognitive-behavioral therapy, psychoeducation, and relaxation training are currently the three mainstream psychological intervention methods (Henschel and Roick, 2020; Moustafa et al., 2021; Ng et al., 2022).

Research indicates that cognitive-behavioral therapy (CBT) is a promising strategy. This approach focuses on helping individuals identify and challenge their negative and irrational thinking patterns, encouraging students to assess mathematical tasks and challenges more objectively, thus alleviating anxiety caused by excessive worry and fear (Moustafa et al., 2021). In the long term, this method can enable students to maintain calmness and rationality when facing mathematical challenges, thereby improving mathematical abilities (Ramirez et al., 2018). Psychoeducation is also an essential intervention measure. It aims to enhance students' understanding of mathematical anxiety, allowing them to better comprehend the causes, characteristics, and impacts of anxiety (Casad et al., 2015). Studies have shown that psychoeducation can help students develop a positive and healthy learning attitude, thus reducing the fear of mathematics (Cheng et al., 2022). Through psychoeducation, students can address mathematical anxiety specifically, establishing a positive emotional connection with mathematics. Relaxation training, on the other hand, starts from a physical perspective, assisting individuals in alleviating the physical and psychological stress generated by mathematics. For instance, techniques such as deep breathing and progressive muscle relaxation have been found to effectively help students maintain psychological balance and reduce tension and anxiety during mathematical learning (Ng et al., 2022).

In conclusion, by integrating the above three strategies, we can assist students in reducing the levels of mathematical anxiety from multiple dimensions. Continuous and systematic psychological interventions are key, enabling individuals to gradually overcome mathematical anxiety and engage in mathematical learning and practice with more confidence and efficiency.

4.5.3 Personalized intervention strategies

In exploring intervention methods for mathematical anxiety and cognitive impairments, personalized intervention strategies have emerged as a focal point receiving significant attention. This strategy emphasizes developing and implementing intervention plans based on each learner's unique characteristics and needs, aiming to provide more precise and targeted assistance.

Firstly, this strategy is based on a clear premise: each learner exhibits variations in cognitive abilities and mathematical anxiety (Li et al., 2021). Research suggests that to effectively address specific problems encountered by learners in mathematical learning, intervention plans must consider the type and degree of learners' cognitive impairments and the manifestation and severity of mathematical anxiety (Luneta and Sunzuma, 2022). Therefore, intervention plans should be meticulously tailored to learners' specific situations. Secondly, personalized intervention strategies are not merely preliminary planning but represent a dynamic, continuously adjusting process. Based on learners' feedback and progress during the intervention, strategies and methods will be timely adjusted to ensure they consistently meet learners' actual needs (Johnson et al., 2020). The flexibility of this strategy not only ensures that interventions always align with learners' needs but also enhances learners' participation and acceptance. Additionally, intervening solely from mathematical anxiety and cognitive perspectives is insufficient. Personalized intervention strategies emphasize a comprehensive focus on learners, providing help not only from a cognitive perspective but also considering learners' psychological, social, and emotional factors, offering holistic support (Reyes, 2019; Shafiq et al., 2021). For example, enhancing learners' self-efficacy and learning motivation, optimizing the learning environment, and strengthening social support are all considerations within this strategy.

In general, personalized intervention strategies emphasize respect for individual differences and support for holistic development, offering effective assistance to learners encountering anxiety and cognitive impairments in mathematical learning. Through the implementation of this strategy, we hope to assist learners in achieving greater progress and development in mathematical learning.

4.5.4 Integrated intervention methods

Integrated intervention methods have increasingly attracted attention as an innovative strategy in the research field of mathematical anxiety and cognitive impairments. Research indicates that this method, by combining cognitive training with psychological interventions, forms a diversified intervention framework aimed at comprehensively improving individuals' mathematical anxiety and cognitive impairments (Soares et al., 2018). Cognitive training focuses on enhancing the efficiency and accuracy of information processing, including training in working memory, executive functions, and attention control, which helps improve performance in mathematical tasks and reduce the cognitive load brought about by mathematical anxiety (Schmidt et al., 2009; Wu et al., 2019; Chatzivasileiou and Drigas, 2022). Psychological interventions focus on emotional management and regulation, helping individuals identify, understand, and regulate negative emotions and thoughts related to mathematical anxiety through methods such as cognitive-behavioral therapy and relaxation training (Henschel and Roick, 2020; Moustafa et al., 2021; Ng et al., 2022). The advantage of integrated intervention methods lies in their comprehensiveness, enabling interventions from both cognitive and emotional dimensions. This strategy helps address the issues of mathematical anxiety and cognitive impairments more effectively. Through integrated interventions, individuals can not only enhance their cognitive abilities but also achieve better management and regulation at the emotional level. Moreover, this method emphasizes individualization and flexibility, allowing for the adjustment and combination of different intervention strategies based on individuals' specific needs, aiming to achieve optimal intervention outcomes. In conclusion, integrated intervention methods provide a new, diversified strategy and approach for the intervention of mathematical anxiety and cognitive impairments. Future research is expected to further explore and optimize this intervention method, hoping to achieve better intervention outcomes in practical applications.

4.5.5 Evaluation of intervention effects

In psychological and educational intervention research, there are various essential methods to evaluate intervention effects. Research indicates that a direct comparison of performance before and after intervention is one of the fundamental methods to evaluate intervention effects, helping to measure changes in relevant indicators such as the level of mathematical anxiety and cognitive abilities (Casad et al., 2015). Meanwhile, comparison with a control group is considered a more precise evaluation method. Through this comparison, the effect of the intervention can be judged more accurately, eliminating other possible interfering factors. Additionally, the importance of long-term tracking should not be overlooked (Bishara and Kaplan, 2021). Long-term tracking can help researchers explore the sustainability and stability of intervention effects, providing a more accurate evaluation of the long-term effects of intervention strategies (Ng et al., 2022). Research should also consider the multidimensionality of evaluation. Multidimensional evaluations, including assessments of individuals' self-efficacy, motivation, and emotional regulation abilities, can provide a more comprehensive and profound understanding of the effects of intervention strategies (Chipman, 2010). By integrating various evaluation methods, a more comprehensive and accurate conclusion can be drawn. In summary, evaluating intervention effects is a complex and multi-level process. Through meticulous and comprehensive evaluation, we can better understand and validate the effectiveness of intervention strategies, providing robust support and valuable references for future research and practice.

In conclusion, intervention strategies for mathematical anxiety and cognitive impairments are diversified and comprehensive. Through continuous research and exploration, we can continually refine and optimize intervention methods, providing more effective support for alleviating mathematical anxiety and improving cognitive impairments.

4.6 Comparison of research methods and results

In the in-depth exploration of the interactive relationship between mathematical anxiety and cognitive impairments, we must confront a reality: significant disparities exist in the research methods and results across various studies. These differences offer us a valuable opportunity to understand this complex phenomenon from multiple angles and dimensions. Below is a detailed comparison and analysis of the research methods and results from various studies.

4.6.1 Diversity of research focus

In exploring the intertwined relationship between mathematical anxiety and cognitive impairments, research exhibits a rich diversity of focuses. Firstly, some studies predominantly concentrate on the neural mechanisms of mathematical anxiety and cognitive impairments, often employing advanced neuroimaging techniques such as functional magnetic resonance imaging (fMRI) and diffusion tensor imaging (DTI) (Newman et al., 2011; Jolles et al., 2015). These studies reveal how mathematical anxiety affects individuals' cognitive processing at the neural level, providing neurobiological evidence for a deeper understanding of the nature of mathematical anxiety and its impact on individuals' mathematical learning abilities. For instance, studies have found that individuals with mathematical anxiety exhibit increased activity in brain regions associated with emotional regulation and decreased activity in regions related to mathematical information processing when handling mathematical tasks (Young et al., 2012). Exploring these neural mechanisms contributes to a deeper understanding of the intrinsic connections between mathematical anxiety and cognitive impairments. On the other hand, some studies focus more on the design and evaluation of intervention strategies, seeking and validating methods to alleviate mathematical anxiety and improve cognitive impairments (Schmidt et al., 2009; Wu et al., 2019; Li et al., 2021; Chatzivasileiou and Drigas, 2022; Ng et al., 2022). For example, by implementing cognitive-behavioral therapy or psychoeducational interventions, these studies aim to reduce students' levels of mathematical anxiety and help improve their mathematical learning outcomes (Bishara and Kaplan, 2021; Moustafa et al., 2021). Research focused on interventions holds practical value and guidance, offering us methods to practically address and improve mathematical anxiety and cognitive impairments.

In consideration of the above, the diversity of research focuses enriches our understanding of the relationship between mathematical anxiety and cognitive impairments. It provides approaches and methods to address and study this issue from different angles and dimensions, contributing to a more comprehensive and profound exploration of the complex relationship between mathematical anxiety and cognitive impairments.

4.6.2 Variability in sample selection

In discussing the relationship between mathematical anxiety and cognitive impairments, the strategies and methods of sample selection hold decisive importance. Through a comprehensive analysis of multiple studies, we find significant variability in sample selection, directly affecting the depth, breadth, and representativeness of the research conclusions.

Firstly, some studies show that researchers have a clear focus on sample selection, specifically choosing participants from certain age groups or backgrounds, such as elementary and high school students, or university students. This targeted selection provides researchers with a more focused perspective, enabling them to delve deeply into the manifestations of mathematical anxiety in specific groups (Zhou et al., 2007; Prado et al., 2014; Jolles et al., 2015). For example, some studies have found that middle school students have higher levels of mathematical anxiety compared to university students, possibly related to their academic pressures and external expectations (Klados et al., 2015). This research method helps accurately reveal the characteristics of mathematical anxiety at different educational stages. However, other studies have adopted a broader sample selection, encompassing various ages, genders, cultures, and educational backgrounds, thus making the research results more universal and representative (Yi-Rong et al., 2011; Jolles et al., 2015). Such a method can help us understand the manifestations of mathematical anxiety in various populations more comprehensively, thereby revealing its general connections with cognitive impairments. More importantly, this broad sample selection provides an opportunity to explore the potential influences of background factors such as culture and education on mathematical anxiety, offering robust guidance for the formulation of effective intervention measures in the future.

In conclusion, the variability in sample selection not only affects the focus and depth of the research but also determines the application and interpretation of the research results. Therefore, future research should pay more attention to sample selection strategies to reveal the relationship between mathematical anxiety and cognitive impairments more precisely, providing more practical references for educational and psychological interventions.

4.6.3 Diversity of data analysis methods

In the relevant research exploring the interactive relationship between mathematical anxiety and cognitive impairments, the diversity of data analysis methods has emerged as a significant characteristic. Many scholars have adopted quantitative analysis methods, utilizing rigorous statistical tests such as t-tests, analysis of variance, and regression analysis to validate research hypotheses, and quantitatively assess the relationship between mathematical anxiety and cognitive impairments based on large sample sizes (Rosenberg-Lee et al., 2011; Soltész et al., 2011; Klados et al., 2017; Choi-Koh and Ryoo, 2019). These studies present results in the form of data and charts, providing intuitive evidence for unveiling the objective relationship between mathematical anxiety and cognitive impairments. Simultaneously, some studies have chosen qualitative analysis methods, collecting data through open-ended questionnaires, in-depth interviews, and focus group discussions, to explore and describe individuals' intrinsic experiences and feelings when facing mathematical learning more profoundly (Young et al., 2012; Batashvili et al., 2019; Peña et al., 2019). This approach focuses on revealing students' genuine reactions and feelings in mathematical learning, providing rich background information for understanding how mathematical anxiety leads to cognitive impairments. Some studies have adopted mixed methods, integrating both quantitative and qualitative analyses, aiming to reveal the interactive relationship between mathematical anxiety and cognitive impairments more comprehensively (Rosenberg-Lee et al., 2011; Young et al., 2012; Peña et al., 2019). This strategy helps obtain a rich diversity of data, allowing for a more comprehensive and profound understanding and interpretation of how mathematical anxiety affects individuals' cognitive processes.

Considering the diversity of these research methods reflects that scholars are exploring the issue of mathematical anxiety and cognitive impairments from various angles and dimensions. This methodological diversity enriches the research content and helps us understand the complex relationship between mathematical anxiety and cognitive impairments more comprehensively and profoundly, allowing for a better grasp of its essence and patterns.

4.6.4 Interpretation and understanding of research results

Through a comprehensive analysis of numerous literature, we find significant disparities in the interpretation and understanding of research on mathematical anxiety and cognitive impairments, mainly reflected in the emphasis on individual differences and the exploration of general rules and mechanisms.

Some studies indicate that individuals, when facing mathematical tasks, exhibit varying degrees of mathematical anxiety and cognitive impairments due to differences in personal experiences and cognitive processing methods (Bulthé et al., 2019). These studies emphasize proposing targeted intervention measures based on individuals' specific situations. For example, providing psychological counseling for individuals who have mathematical anxiety due to past failures, and offering learning guidance and strategy training for those lacking effective learning strategies. On the other hand, some studies focus more on exploring the general rules and mechanisms of mathematical anxiety and cognitive impairments, trying to find universal solutions to guide teaching and intervention (Li et al., 2013; Foley et al., 2017; Klados et al., 2019). For instance, enhancing students' self-efficacy and autonomous learning abilities is considered an effective way to alleviate mathematical anxiety and improve cognitive impairments.

To achieve more comprehensive and effective teaching and intervention, future research should find a balance between individual differences and general rules. We should consider each student's uniqueness, providing personalized support that meets their needs, while also exploring the common rules of mathematical anxiety and cognitive impairments, forming systematic and scientific teaching and intervention strategies. This integrated approach helps students overcome mathematical anxiety and cognitive impairments more effectively, thereby improving the effectiveness and quality of mathematical learning.

In conclusion, the differences in research methods and results across various literature provide us with a valuable perspective to understand the interactive relationship between mathematical anxiety and cognitive impairments from multiple angles and dimensions. This diversity and complexity require us to consider various factors comprehensively when analyzing and comparing, allowing for a more comprehensive and profound understanding of the current research status and development trends in this field.

4.7 Limitations

In the current academic environment, significant progress has been made in the research on mathematical cognitive impairments and math anxiety. However, as with many academic studies, research in this field also has its inherent limitations. Below is a detailed discussion of these limitations:

4.7.1 Issue of sample size

For studies in the neuroscience field exploring the relationship between math anxiety and cognitive processes, the size and representativeness of the sample constitute significant limitations.

Firstly, a smaller sample might lead to Type II errors, where an actual effect is not detected due to insufficient sample size. Such limitation could cause researchers to erroneously conclude that there is no association between math anxiety and a particular cognitive process when, in fact, such an association might exist. Additionally, another notable limitation of a small sample is its impact on the replicability of research results. Specific samples might make the results too dependent on that sample, questioning the applicability in a broader population. Secondly, the representativeness of the research sample is another critical limitation. If the research sample lacks diversity, such as being limited to specific age groups, genders, or cultural backgrounds, it might make the research results less universally applicable. For instance, studies involving only university students might not be generalizable to other age groups, constituting its limitation. Practical research conditions and constraints, such as funding, time, and technology, often further exacerbate these limitations. High costs and technical difficulties might limit the number and diversity of recruitable samples, especially in studies involving high-cost technologies such as functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy (fNIRS) (Artemenko et al., 2019; Shi et al., 2023).

In conclusion, despite the unique value of neuroscience research, the limitations in sample size and representativeness need full recognition and attention. Researchers should consider these limitations when assessing the reliability and universality of their research results and seek methods to address or mitigate these issues where possible.

4.7.2 Diversity of research methods

In the research on math anxiety and cognitive impairments, a variety of research methods have been employed, including functional magnetic resonance imaging (fMRI), event-related potentials (ERP), behavioral assessment tools, and functional near-infrared spectroscopy (fNIRS). Each of these methods has its unique advantages and limitations, collectively constituting a rich research toolbox, allowing for an in-depth exploration of such complex phenomena from multiple angles.

Firstly, fMRI, with its high spatial resolution, can capture real-time brain activity during mathematical tasks, but its main limitation lies in the inability to directly measure neuronal activity, and it is relatively costly (Holloway et al., 2013). ERP, with its high temporal resolution, can measure the brain's immediate response to specific stimuli or events, but its spatial resolution is lower, and the source of signals might be challenging to determine (Klados et al., 2015). Behavioral assessment tools are relatively simple, low-cost, and suitable for large-sample research but might not fully reveal individuals' intrinsic cognitive and emotional processes.

However, the diversity of these methods also brings challenges to research. Different research methods might lead to different interpretations and conclusions regarding the same phenomenon. For example, an fMRI-based study might reveal that a particular brain area is more active in individuals with math anxiety (Newman et al., 2011), while an ERP-based study might find that this activity is related to a specific cognitive process (Peña and Suárez-Pellicioni, 2014). Moreover, since each method has its inherent limitations, such as dependency on technology and equipment, influence of experimental conditions and analysis methods, and interference of cultural, educational backgrounds, and individual differences, researchers need to apply multiple methods comprehensively to understand math anxiety and cognitive impairments more accurately and thoroughly. Through cross-validation and integrated analysis, more in-depth and comprehensive research results are expected to be obtained.

4.7.3 Limitations in research focus

In the field of research on mathematical cognitive impairments and math anxiety, the current focus predominantly lies on fundamental mathematical skills, such as basic computational abilities and numerical representation (Rosenberg-Lee et al., 2011; Prado et al., 2014; Jolles et al., 2015). The limitation of this focus manifests as a relative neglect of more advanced and complex mathematical cognitive processes, such as abstract thinking, problem-solving, and logical reasoning. This not only may constrain a more comprehensive and profound understanding of math anxiety and mathematical cognitive impairments but also may adversely impact the design and implementation of educational practices and intervention strategies.

Firstly, while fundamental mathematical skills are the basis of mathematical learning, focusing solely on them might overlook the diversity and complexity of mathematical cognition. For instance, abilities like abstract thinking and problem-solving are essential for understanding and mastering mathematical concepts, conducting mathematical reasoning, and solving complex problems. Secondly, the current research focus might also limit a more comprehensive exploration of math anxiety and mathematical cognitive impairments, as these issues are related not only to basic skills but also to more advanced mathematical cognitive processes.

Moreover, an excessive focus on fundamental skills might lead to a monotonous and one-sided orientation in educational and intervention strategies, affecting their comprehensive effectiveness. For more effective promotion of mathematical learning and alleviation of math anxiety, research and practice need to consider the comprehensiveness and diversity of mathematical cognition.

In conclusion, research should pay balanced attention to both fundamental skills and advanced mathematical cognitive processes, to promote comprehensive theoretical and practical development in the field of mathematical cognitive impairments and math anxiety. Future research needs to explore more deeply various aspects of mathematical cognition, including complex and advanced cognitive processes beyond basic skills. This way, we can understand math anxiety and mathematical cognitive impairments more comprehensively and provide richer and more comprehensive guidance for educational practice and intervention strategies.

4.7.4 Issues in interdisciplinary integration

Researching the complex and multifaceted topic of mathematical cognitive impairments and math anxiety involves the intersection of numerous disciplines such as psychology, education, and neuroscience. Although each discipline provides unique and rich perspectives, efficiently integrating these diverse resources has become a core challenge. The primary issue lies in the independent characteristics and focuses of the research methods and theoretical frameworks of each discipline. Psychology mainly studies individuals' psychological and behavioral responses, neuroscience focuses on exploring biological mechanisms and neural networks, and education emphasizes the effects of teaching methods and educational environments on individuals. This requires researchers to meticulously adjust and integrate the features of each discipline when designing and implementing research. Secondly, successful interdisciplinary research requires researchers to possess high levels of collaboration and communication skills. This not only demands them to understand and master the core knowledge and methods of each discipline but also to establish effective communication and cooperation with peers from different disciplinary backgrounds, undoubtedly setting higher requirements for researchers' professional competence and interdisciplinary collaboration abilities. Moreover, finding a balance to maintain the uniqueness of each discipline while achieving effective integration is also crucial. Excessive integration might weaken the core advantages of a discipline, while insufficient integration might lead to one-sided or limited research results.

In conclusion, we recognize that interdisciplinary integration in the research of mathematical cognitive impairments and math anxiety is both an essential direction and a challenging task. To obtain more comprehensive and profound research results in this field, we must innovate in theory and methods and strengthen communication and cooperation between disciplines.

4.7.5 Lack of intervention strategies

In the field of research on math anxiety and cognitive impairments, despite the accumulation of rich theoretical knowledge and empirical data, the effective transformation of this knowledge into practical intervention strategies remains a challenge. Currently, although there is a deeper description and explanation of math anxiety and cognitive impairments, practical intervention strategies, whether at the educational, psychological, or neurobiological levels, still appear relatively weak. This poses significant constraints on the application in actual education and psychological health fields.

Firstly, most studies focus on the manifestations and causes of math anxiety and cognitive impairments, with less involvement in specific intervention strategies and methods (Li et al., 2013; Foley et al., 2017; Klados et al., 2019). This necessitates further empirical research to explore and confirm the actual effects of various intervention strategies. Secondly, even if some strategies achieve preliminary effects in the short term, their sustainability and stability remain unknown due to the lack of long-term follow-up evaluations. Future research must pay more attention to evaluating the long-term effects of intervention strategies and exploring how these strategies can be sustainably applied in daily environments. Moreover, given the significant variations in math anxiety and cognitive impairments among individuals, intervention strategies also need to have a certain level of individualization and customization. How to adjust and optimize strategies based on individual differences will be key in future research. Additionally, the implementation of intervention strategies also faces various practical challenges, such as resource allocation, professional training, and integration with current education and mental health services. Solving these challenges requires interdisciplinary efforts and cooperation.

In conclusion, despite a deeper understanding of math anxiety and cognitive impairments, there are still many difficulties to overcome in the research and application of intervention strategies. It is hoped that future research can provide more guiding and practical strategies and methods for this field.

4.7.6 Influence of cultural and social background

When exploring math anxiety and mathematical cognitive impairments, the role of cultural and social backgrounds is indispensable. Both play a key role in determining individuals' cognitive development and emotional experiences in the mathematical learning process. However, current research mainly focuses on specific cultural and social environments, providing us with limited perspectives (Yi-Rong et al., 2011; Jolles et al., 2015).

Cultural backgrounds profoundly influence the shaping of mathematical cognition, reflected in different cultures' educational methods, educational emphases, and resource allocations. For instance, some cultures might value basic mathematical skills more, while others might emphasize problem-solving and critical thinking abilities. This implies that the formation of mathematical cognition might vary across different cultures. Social backgrounds also significantly impact math anxiety and mathematical cognitive impairments. They determine societal expectations of mathematical abilities, the social value of mathematical learning, and the general acceptance of math anxiety. For example, some societies might view mathematics as a key competence, while others might not. Furthermore, cultural and social backgrounds also affect how individuals perceive and cope with math anxiety and mathematical cognitive impairments. In some cultures, people might be more willing to openly discuss their difficulties, while in others, they might choose to remain silent about these issues.

In summary, to deeply understand math anxiety and mathematical cognitive impairments, we need to consider a broader cultural and social background. Future research should pay more attention to the diversity of these factors, which can not only provide us with a deeper understanding but also help in formulating more effective and targeted intervention strategies.

In conclusion, although some progress has been made in the research of mathematical cognitive impairments and math anxiety, there are still many unresolved issues and challenges. These limitations remind us to be cautious in interpreting and applying research results and provide direction for future research.

4.8 Future research directions

Based on the review and analysis of existing literature, it is evident that math anxiety and cognitive impairments are two important and interconnected research focuses in the field of mathematical cognition. Future research can further expand and deepen in the following directions:

4.8.1 In-depth study of math anxiety

(1) Exploration of neural mechanisms

To deeply understand the neural mechanisms behind math anxiety, future research should focus on revealing how neurotransmitter changes and synaptic plasticity influence the onset and maintenance of math anxiety. Current research has somewhat demonstrated the association between math anxiety and brain activity patterns through functional brain imaging technologies, but a comprehensive understanding of the neurobiological foundations is still pending. Neurotransmitters such as serotonin, dopamine, and cortisol may play crucial roles in math anxiety. Therefore, there should be a profound exploration of how these neurotransmitters influence the levels of math anxiety and whether they can serve as potential targets for alleviating math anxiety. Additionally, research should assess whether there are abnormalities in the synaptic plasticity of individuals with math anxiety and explore whether these abnormalities are related to the clinical manifestations of math anxiety, thereby providing a more comprehensive and refined theoretical basis for future interventions against math anxiety.

(2) Optimization of intervention strategies

For math anxiety, future research should delve deeper into the optimization and sustainability of intervention strategies. Firstly, the range of intervention methods should be broadened. In addition to cognitive-behavioral therapy, psychoeducation, and relaxation training, considerations could be given to introducing psychodynamic therapy and acceptance and commitment therapy, enriching the diversity of interventions. Simultaneously, research should consider the combined use of different intervention methods to enhance the overall effect of the interventions. Secondly, the focus of research needs to extend from the short-term effects of interventions to long-term effects. Research should conduct long-term follow-ups to comprehensively assess the sustainability and stability of intervention strategies, ensuring their long-term application. Lastly, future research should also deeply understand the mechanisms of intervention actions, clarifying the precise pathways of their effects, and further optimizing the targeting and selection of intervention methods. Through these in-depth studies, it is expected to find more precise and effective strategies, providing continuous and comprehensive support for individuals troubled by math anxiety.

4.8.2 Multidimensional exploration of cognitive impairments

(1) Improvement of diagnostic and assessment tools

Future research on cognitive impairments should focus on the multidimensional improvement and innovation of diagnostic and assessment tools. Firstly, research should focus on developing more accurate and sensitive diagnostic assessment tools. This involves not only the development of new psychological measurement tools but also the revision and optimization of existing tools to assess individuals' cognitive impairments more comprehensively and accurately. Secondly, more advanced neuroimaging technologies should be utilized to deeply explore and assess cognitive impairments from a neurobiological perspective, aiming to reveal their deeper neural mechanisms. Lastly, by introducing machine learning and artificial intelligence technologies, significant information for diagnosing and assessing cognitive impairments can be identified in big data. By building and training more accurate predictive models, the risk and severity of cognitive impairments can be identified and assessed more effectively. The comprehensive application of these methods and technologies will help improve the accuracy and sensitivity of the diagnosis and assessment of cognitive impairments.

(2) Personalized intervention plans

The direction of future research should focus on the multidimensional exploration of cognitive impairments, especially in formulating personalized intervention plans. For different types and degrees of cognitive impairments, research should design more specific and targeted intervention strategies. For example, interventions for mild cognitive impairments can adopt more gentle and heuristic methods, while severe cognitive impairments require more intensive and systematic strategies. Additionally, the formulation of intervention plans should also fully consider individual differences, such as age, gender, educational background, and psychological characteristics. Thus, by integrating various factors, intervention plans can be more refined and personalized, thereby effectively improving the effectiveness and efficiency of interventions, promoting the improvement and recovery of individuals with cognitive impairments.

4.8.3 Interaction research between math anxiety and cognitive impairments

(1) Exploration of mutual influence mechanisms

An essential direction for future research is to delve deeply into the interaction mechanisms between math anxiety and cognitive impairments. Firstly, research should reveal more precisely how math anxiety affects individuals' performance in cognitive processes such as working memory, attention allocation, and information processing speed, and how this indirectly leads to the emergence and exacerbation of cognitive impairments. Simultaneously, attention should be given to how cognitive impairments become a source of math anxiety, considering how they enhance individuals' math anxiety by causing learning difficulties and declining academic performance.

From a neurobiological perspective, future research could explore the common neural foundations of math anxiety and cognitive impairments. For instance, by utilizing brain imaging technologies, the similarities and differences in brain activity and connection patterns between math anxiety and cognitive impairments could be revealed. Also, considerations should be given to exploring their mutual influences on behavioral performances and learning strategies from psychological and educational perspectives. By integrating research methods and perspectives from different disciplines, a more comprehensive understanding of the interactions between math anxiety and cognitive impairments is expected, providing theoretical support for alleviating math anxiety and improving cognitive impairments.

(2) Comprehensive intervention strategies

Regarding the interactive relationship between math anxiety and cognitive impairments, the direction of future research should focus on developing comprehensive intervention strategies to address these two issues bidirectionally. Firstly, for math anxiety, psychological intervention strategies such as cognitive-behavioral therapy, psychoeducation, and relaxation training can be adopted to help individuals stabilize emotions and reduce anxiety levels. Simultaneously, to address cognitive impairments, educational interventions like metacognitive strategy training, problem-solving strategy training, and learning strategy guidance will be effective. A more innovative research direction might involve combining the aforementioned psychological and educational interventions to form a comprehensive intervention model. For example, integrating specific training for cognitive impairments into psychological interventions, or incorporating psychological support for math anxiety into educational interventions. Such comprehensive strategies can not only achieve comprehensive improvements in math anxiety and cognitive impairments but also contribute to providing a more systematic, in-depth understanding and intervention methods for these two major issues.

4.8.4 Interdisciplinary collaborative research

In today's complex and ever-changing academic research field, interdisciplinary collaborative research has become a trend and necessity, especially on cross-disciplinary issues like math anxiety and cognitive impairments, where experts and scholars from various disciplines need to join hands for exploration and research.

(1) Interdisciplinary integration

Future research on math anxiety should emphasize interdisciplinary integration and collaboration. Math anxiety is not merely a problem in the field of psychology; it is closely related to brain structure and function, educational methods, and individual psychology and emotional responses. Neuroscientists can explore how math anxiety affects brain activity using advanced brain imaging technologies, providing a scientific basis for formulating corresponding intervention measures. Educators can delve deeply into educational methods and strategies, exploring how to reduce the incidence of math anxiety through educational interventions and applying research findings to educational practice. The contribution of psychologists lies in deeply analyzing the psychological mechanisms of math anxiety, studying its association with other psychological problems, and looking for possibilities of comprehensive interventions. This interdisciplinary collaboration helps us understand the causes of math anxiety from different dimensions and levels comprehensively and find more effective intervention methods.

(2) International collaboration

With the acceleration of globalization, research on math anxiety and cognitive impairments also shows an increasingly international trend. Faced with this global issue, the importance of interdisciplinary and international collaboration becomes more prominent. International collaboration not only promotes resource sharing, improving research efficiency and quality, but also broadens research perspectives through the exchange and collision of different cultures and educational backgrounds, leading to the exploration of new research directions and methods. More importantly, international collaboration can promote the global dissemination and application of research findings, providing global strategies for solving problems of math anxiety and cognitive impairments. In conclusion, through deepening interdisciplinary integration and international collaboration, we can expect to promote the progress of research on math anxiety and cognitive impairments more quickly and effectively, providing more scientific and practical theoretical support and strategic suggestions for related educational practices.

Through in-depth research in the above directions, we can expect richer and more profound research findings in the fields of math anxiety and cognitive impairments, providing more scientific and effective theoretical support and strategic suggestions for educational practices.

5 Conclusion

5.1 Main findings

This review systematically analyzes a wealth of related literature, aiming to deeply explore the core roles of math anxiety and cognitive impairments in mathematical cognition processes and their interconnections. In terms of cognitive impairments, the study reveals two primary forms of impediments: developmental calculation disorders and acquired calculation disorders. The former typically manifests as inherent calculation deficiencies without apparent neurophysiological damage, while the latter usually results from some form of brain injury or disease causing the loss or decline of calculation abilities. However, appropriate training and intervention strategies may help improve or alleviate the symptoms of these impediments.

Regarding math anxiety, this phenomenon plays a crucial role in mathematical cognitive processes. Math anxiety not only affects the representation of numbers and calculations but also interferes with the resolution of arithmetic problems and spatial processing abilities. Individuals suffering from math anxiety may find mathematical tasks more challenging, leading to increased psychological stress and further decline in mathematical performance.

By integrating these findings, this article helps comprehensively understand how math anxiety and cognitive impairments mutually influence mathematical cognition at multiple levels. This understanding not only deepens our exploration of the psychological and neural mechanisms of mathematical cognition but also provides theoretical support for formulating precise and effective educational intervention strategies for various types of mathematical difficulties. Future research should further explore how to help individuals affected by math anxiety and cognitive impairments more effectively through integrated intervention methods, promoting their mathematical learning and self-development.

5.2 Practical applications

The profound findings of this study offer valuable insights into the educational field, especially concerning resolving students' math anxiety and cognitive impairment issues. Firstly, for students with cognitive impairments, educators can design targeted and personalized teaching strategies and intervention measures based on individual differences. For instance, creating a more supportive learning environment and providing abundant practical opportunities to enhance their mathematical cognitive abilities, while stimulating students' learning enthusiasm and confidence through cooperative learning and group discussions. Secondly, to alleviate students' math anxiety, educators should strengthen care and support, helping students gradually overcome anxiety through more guiding and encouraging methods. Introducing lively and interesting teaching methods, such as games and stories, is also an effective way to improve students' learning interest and participation. Additionally, educators can flexibly adjust teaching strategies to meet the specific needs of different students. For example, integrating more practical applications and case analyses into teaching, allowing students to feel the practicality of mathematical learning, enhancing learning enthusiasm and motivation. Simultaneously, through regular feedback and evaluation, educators can timely grasp students' learning conditions, make corresponding teaching adjustments, and meet students' learning needs more precisely.

In summary, this study provides educators with theoretical support and strategic guidance for practically addressing students' math anxiety and cognitive impairments. Educators should fully utilize these research findings, scientifically and reasonably design and implement teaching activities, aiming to improve students' mathematical cognitive abilities and learning outcomes, helping them overcome difficulties and challenges in the learning process.

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