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MISCONCEPTIONS ON FRACTIONS, ALGEBRAIC VARIABLES, AND FUNCTIONS IN MATHEMATICS EDUCATION: A 2016-2026 SYSTEMATIC LITERATURE REVIEW OF PREVALENCE, ROOT CAUSES, AND INTERVENTION EFFECTIVENESS

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ABSTRACT

Misconceptions in mathematics education are a persistent problem with far-reaching implications across all levels of education, from preschool through higher education. This study narrows the focus on misconceptions to three main clusters that are frequently encountered and have the greatest impact on mathematics education: fractions, algebraic variables, and functions. This study aims to identify the most common forms of misconceptions, their underlying patterns, and interventions proven effective in reducing misconceptions within these three priority clusters. Using a Systematic Literature Review (SLR) approach in accordance with the PRISMA 2020 guidelines, the search was conducted across three databases, such as Scopus, ERIC, and SpringerLink, yielding 117,846 initial records. Following a multi-stage screening process, 31 articles published between 2016 and 2026 were analysed in depth. The review results indicate that the most prevalent misconceptions are related to fractions, algebraic variables, and functions. Regarding interventions, the use of technological tools such as GeoGebra, inquiry-based learning, cognitive conflict, and a bilingual approach was frequently found to have demonstrated positive effects across studies. These findings have important implications for curriculum design, teacher professional development, and the design of learning environments that are adaptive and responsive to the diversity of students' prior conceptions.

Keywords: Learning Interventions, Mathematics Education, Mathematics Misconceptions, PRISMA, Systematic Literature Review.

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PRELIMINARY

Mathematics is one of the fundamental disciplines that serves as the foundation for the development of science and technology. Therefore, mastering its core principles is essential for fostering logical reasoning and technological literacy (Mullis et al., 2021). However, it has long been recognized that mathematics learning is inseparable from the issue of misconceptions. Misconceptions defined as understandings that consistently differ from scientifically accepted concepts (Ningsih et al., 2019). Unlike random errors, misconceptions are systematic and structured, making them more difficult to identify and correct.

Misconceptions can occur at all levels of education, from early childhood students that just learning numbers to advanced college students that studying calculus or linear algebra. Furthermore, misconceptions do not occur only among students, but also among teachers and prospective teachers, who in turn may pass on these misconceptions to the next generation. Therefore, identifying and addressing misconceptions is an urgent pedagogical challenge.

Although misconceptions occur across various topics and grade levels, recent empirical evidence indicates that the greatest burden on curricular achievement in secondary education (junior high and senior high school) is concentrated in three clusters: (i) fractions, which involve the multiple meanings of five interpretations (part–whole, quotient, ratio, operator, and measure) as well as counterintuitive operations; (ii) algebraic variables (*letter-as-object*), where students treat letters as labels for fixed objects rather than quantities that can change; and (iii) functions and graphs, where students interpret curves as literal images rather than representations of mathematical relationships. These three clusters were selected as the primary focus of the study due to their high prevalence, strong longitudinal impact on advanced topics such as equations and calculus, and the availability of interventions that allow for replication.

This study does not aim to comprehensively map all mathematical misconceptions, but rather addresses the specific questions of why these three clusters persist despite repeated instruction across various curricula, and what interventions have consistently proven effective in the context of secondary education. Previous studies on mathematical misconceptions have three main limitations: (1) most catalog the types of misconceptions without linking them to causal mechanisms that are consistent across studies; (2) intervention evaluations are conducted in single contexts without comparing relative effects across topics and grade levels; and (3) the resulting recommendations are rarely operational and directly actionable by teachers in the classroom. This SLR fills these gaps by presenting a synthesis of common causal mechanisms and a matrix of concrete instructional implications.

The original contribution of this study lies in three aspects. First, integrates three misconceptions, fractions, algebraic variables, and functions; second, a synthesis of causal patterns across studies for three priority clusters of misconceptions (rather than merely a list of findings); third, a comparison of intervention effectiveness that goes beyond the context of a single study; and fourth, a four-step set of recommendations designed so that middle school mathematics teachers can immediately apply them in the classroom. Based on the above, this study poses two main questions:(1) What are the prevalence patterns and primary causes of misconceptions regarding fractions, algebraic variables *(letter-as-object)*, and functions/graphs in secondary education? (2) Which interventions are most effective, and under what conditions (tools, language, task design) are they most effective for reducing misconceptions within these three clusters?

METHODS

Research Approach and Design

This study uses a Systematic Literature Review (SLR) approach following the PRISMA 2020 guidelines, chosen for its ability to systematically and transparently synthesize empirical evidence in a replicable way, allowing identification of consistent patterns across studies while minimizing selection bias.

Inclusion and Exclusion Criteria

Articles were included if they were published between 2016 and 2026, written in English, openly accessible, directly related to one of the three misconception clusters (fractions, algebraic variables, or functions/graphs) or to interventions addressing them, and were not themselves review or meta-analytic studies. Articles were excluded if they were duplicates, published outside the specified time range, lacked accessible full text, did not report outcome measures mappable to the target misconceptions, or employed diagnostic instruments without documented reliability or validity.

Data Sources and Search Strategy

The literature search was conducted across three major databases, Scopus, ERIC, and SpringerLink, using the search string ("misconception") AND ("mathematics education" OR "mathematics learning" OR "mathematics teaching" OR "math education"), which initially yielded 235,692 records. A first-stage screening applying filters for publication year (2016–2026), subject area (social sciences and multidisciplinary), and document type (articles and conference papers) narrowed this to 9,019 articles. A second-stage screening based on relevant keywords, English-language publication, and open-access availability further reduced the pool to 1,177 articles. These were then screened for topical relevance with the assistance of ChatGPT, yielding 47 candidate articles, which underwent full-text manual review, resulting in a final set of 31 articles that met all eligibility criteria.

Transparency of the Selection Process and Quality Appraisal

The selection process consists of three stages: (1) screening of titles and abstracts based on relevance to the three clusters; (2) reading of the full text to ensure content suitability; and (3) appraisal of article quality. The quality appraisal rubric was adapted from the Mixed Methods Appraisal Tool (MMAT) and the Joanna Briggs Institute (JBI), covering five dimensions: (a) alignment of the research design with the study's objectives, (b) clarity of the description of the context and participants, (c) validity and reliability of the diagnostic tools used (e.g., two-tier test, CRI), (d) clarity of the intervention description (materials, duration, implementation fidelity), and (e) adequacy of the analysis and reporting of results.

PRISMA Diagram

The study selection process is illustrated in the following PRISMA 2020 diagram:

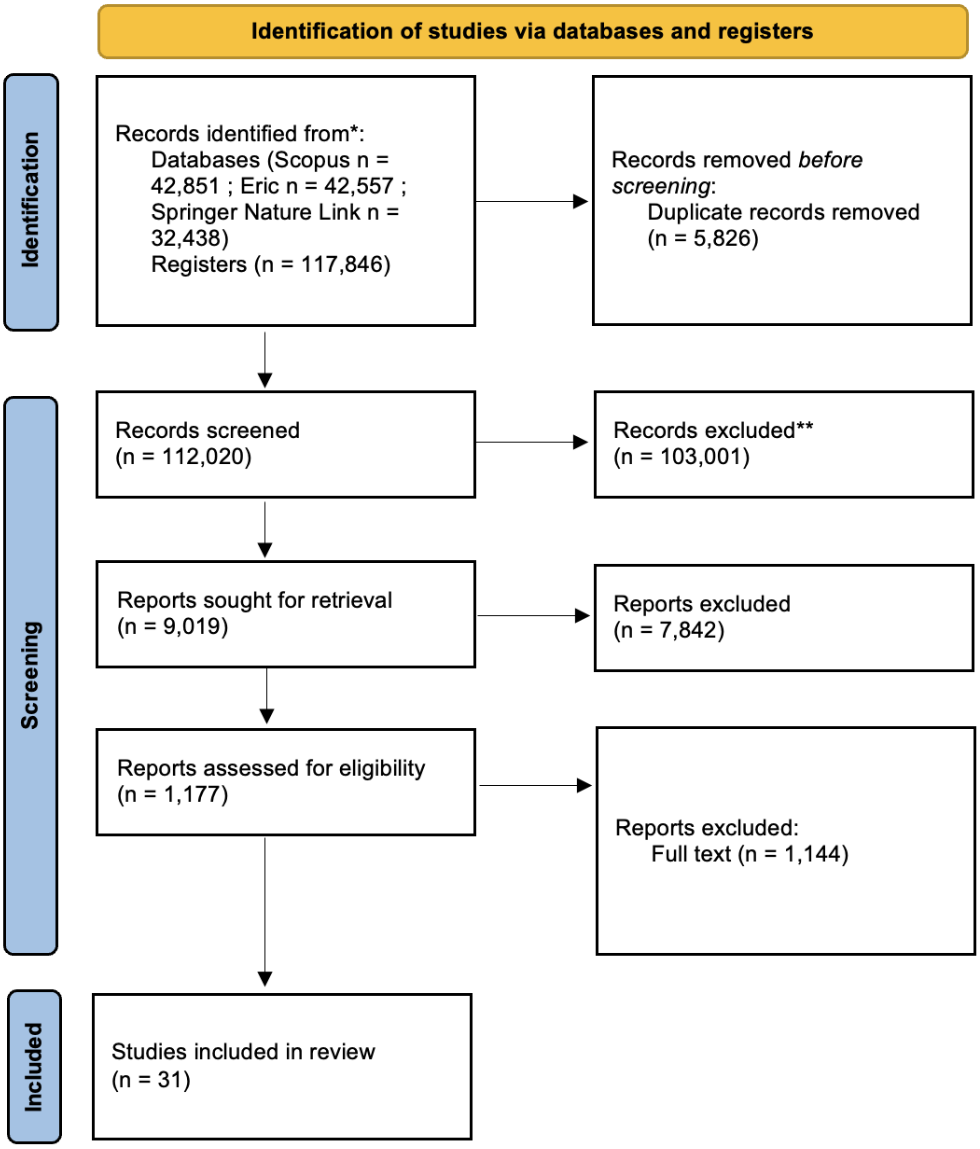

Figure 1. PRISMA 2020 Diagram

Data Extraction and Analysis

Data were systematically extracted, including: title, author, educational level, research method, mathematical topics studied, types of misconceptions identified, interventions used, and main findings. The analysis was conducted thematically using the three-dimensional mechanism framework from : (1) representational (fractions), (2) symbolic (letter-as-object), and (3) graphical mapping (functions/graphs). Additionally, a comparison of intervention effects across studies was conducted to address the second research question.

RESULT AND DISCUSSION

Of the 31 studies analyzed, there was a wide range of educational levels, geographic contexts, and research methodologies. The studies covered levels ranging from preschool/early childhood education (2 studies), elementary school (6 studies), junior high school (7 studies), high school (7 studies), to higher education (9 studies). Geographically, the studies originated from various parts of the world, including Southeast Asia, Africa, Europe, the United States, and Australia. In terms of methodology, 12 studies used a qualitative approach, 10 used a quantitative approach, and 9 used *mixed methods*. Table 1 below presents a summary of the characteristics of all 31 studies included in this review:

Table 1. Characteristics of the Studies Reviewed (n = 31)

No	Authors	Years	Education Level	Method	Key Findings
1	Haryono et al.	2024	High School	Pre-experimental; CRI	Misconceptions decreased by 26.50% (from 54% to 27.50%) after collaborative e-learning
2	Ramadianti, W. et al.	2019	Junior High School	Qualitative; content analysis	Misconceptions were found in all aspects of fraction interpretation; limited context in understanding fractions
3	Çelikkaya & Kürümlüoğlu	2025	6th Grade Elementary/ Junior High School	Action research	Action research effectively eliminates misconceptions about democracy
4	Turmuzi, M. et al.	2025	Higher Education	Qualitative; CRI; Case	21.69% of students have misconceptions; learning style & gender have an effect; Google Classroom is not yet optimal

No	Authors	Years	Education Level	Method	Key Findings
5	Munyaruhengeri et al.	2024	High School	Qualitative; survey	Significant misconceptions regarding limits and continuity of functions; difficulties with the concept of discontinuity
6	Ngoveni, M.A.	2025	TVET Level 2	Qualitative; Document analysis	76% structural errors; 22% executive errors; pedagogical intervention is required
7	Matindike & Makonye	2024	Grade 11 High School	Qualitative; APOS theory	5 categories of misconceptions: algebraic, conceptual, asymptotes, graphs, notation; exploration & discovery recommended
8	Klingbeil & Moons	2025	Junior High School (7–8)	Quantitative; Latent Transition Analysis	Most students exhibit the Letter-as-Object misconception; it persists after algebra instruction
9	Mutambara & Bansilal	2024	Higher Education	Qualitative; case study	Misconceptions lead to procedural, conceptual, and fundamental errors in linear independence
10	Eleftheriadi et al.	2023	Early Childhood Education (ages 4–6)	Qualitative; case study	Misconceptions about numbers and operations are found from an early age; they differ across age groups
11	Potvin & Cyr	2017	Multi-level	Quantitative; cross-sectional	Persistent misconceptions even at high levels of expertise; coexistence with scientific knowledge
12	Hendricks & Olawale	2023	Senior High School (10–12)	Quantitative; survei	The frequency of probability misconceptions varies across classes; male students tend to have more misconceptions
13	Makonye & Fakude	2016	8th Grade Junior High School	Qualitative; content analysis	83.3% misconceptions; 67% strategic errors; lack of number line mediation
14	Lin, Y.-C. et al.	2024	6th Grade Elementary School	Quantitative; WTTT-NS	Only 22.9% of students correctly used the number sense method; WTTT-NS effectively detected misconceptions
15	Seloane et al.	2025	Higher Education	Mixed methods;	GeoGebra effectively addresses misconceptions

No	Authors	Years	Education Level	Method	Key Findings
				quasi-experimental	about complex numbers; improved conceptual understanding
16	Copur-Gencturk, Y.	2021	Elementary School Teacher Education	Quantitative; national survey	Teachers' understanding of basic fraction operations, particularly division; experienced teachers have a deeper understanding
17	Schüler-Meyer et al.	2019	Junior High School (Grade 7)	Mixed methods; quasi-experimental	Bilingual intervention effectively builds conceptual understanding of fractions even without formal proficiency in the native language
18	Zeybek, N.	2026	Higher Education	Teaching experiment; Qualitative	PSTs develop positive dispositions; cognitive conflict as the primary criterion for the transformation of misconceptions
19	Wildgans-Lang et al.	2020	Elementary School Teacher Education	Quantitative; computer simulation	Diagnostic accuracy is quite good but there is significant variability in the diagnostic process
20	Gabler & Ufer	2021	2th Grade Elementary School	Qualitative; longitudinal	Macro-scaffolding intervention effectively develops students' flexibility in additive word problems
21	Leuenberger et al.	2024	1th Grade Elementary School	Quantitative; intervention study	A combination of cooperative learning and individual support is most effective for low-ability students
22	Uegatani et al.	2024	8th Grade Junior High School	Qualitative; theoretical study	It is important to distinguish between 'real' and 'illusionary' difficulties; the transition of awareness is crucial in learning
23	Xu & Ball	2022	K-12 Curriculum	Qualitative; argumentative	Misconceptions about Indigenous mathematics persist; the 2022 Australian curriculum begins to incorporate Indigenous content
24	Segura et al.	2024	Teacher Education	Mixed methods	Recurring difficulties in modeling problem posing; source content influences formulation strategies

No	Authors	Years	Education Level	Method	Key Findings
25	Sajka, M.	2024	Multi-level	Mixed methods; eye-tracking	8 types of 'graph as picture' misconceptions; success rate 0.43; graphs misinterpreted as literal images
26	Ayeh, I.G.	2025	11th Grade Senior High School	Qualitative; clinical interview	Instructional interventions reinforce conceptual understanding of functions; over-reliance on procedures
27	Siantuba et al.	2023	Higher Education	Quantitative; quasi-experimental	Misconception-based inquiry with a digital lab is more effective than the control; conceptual changes are better
28	Gregersen, R.M.	2024	Junior High School	Qualitative; case study	GeoGebra promotes reasoning based on conceptual knowledge; predicting dynamic behavior enhances justification
29	Chytas et al.	2024	Senior High School	Mixed methods; intervention	Most students mastered CT in calculus; the integration of CT and mathematics is feasible and increases interest
30	Zhang et al.	2025	Kindergarten/ Early Childhood Education	Qualitative; educational experiment	Questioning strategies in Conceptual PlayWorld support spatial reasoning and collaborative problem-solving
31	Kobak Demir, M.	2025	Higher Education	Qualitative; case study	55 different misconceptions about STEM; prospective teachers view STEM in a narrow, technology-oriented way

Prevalence Patterns and Primary Causal Mechanisms

An analysis of 31 studies not only revealed dominant clusters of misconceptions but also allowed for the identification of causal mechanisms consistent across studies. The following is a synthesis based on three focus clusters.

a) Misconceptions about *Fractions*

Misconceptions related to fractions emerged as the most frequently reported category. Ramadianti et al. (2019) found that junior high school students held misconceptions across all aspects of fraction interpretation, including fractions as parts of a whole, quotients, ratios, operators, and measures. Copur-Gencturk (2021) revealed that even elementary school teachers have limited conceptual understanding of fraction operations, particularly in fraction division. Furthermore, Schüler-Meyer et al. (2019) demonstrated that fraction misconceptions among multilingual students can be addressed through a bilingual teaching approach.

The coexistence of five interpretations of fractions creates a high *representational load*. When students master only one interpretation (e.g., part-whole), they apply the algorithm appropriate for that interpretation to all contexts, including those that require a different interpretation (e.g., ratios or operators). The absence of an explicit visual-symbolic bridge reinforces this tendency, leading to *the misapplication of* misconceptions *across contexts* (Copur-Gencturk, 2021; Ramadianti et al., 2019).

b) Misconceptions in Algebraic Variables

The most prominent algebraic misconception is *the "Letter-as-Object"* phenomenon, in which students treat algebraic variables as concrete objects rather than quantities that can change. Klingbeil and Moons (2025) used Multilevel Latent Transition Analysis on 2,220 seventh- and eighth-grade students and found that the majority exhibited this misconception, which persisted even after algebra instruction. Ngoveni (2025) found a similar pattern in the context of factorization, where 76% of errors were structural rather than random.

In algebra, letters *are reified*, that is, treated as fixed concrete objects (e.g., "a = apple") rather than symbols representing variable quantities. The lack of learning experiences that emphasize variability, generalization, and parameter–solution relationships hinders the cognitive shift from the *iconic* stage to the *symbolic* stage. The persistence of these misconceptions even after formal instruction (Klingbeil & Moons, 2025) suggests that introducing notation without accompanying activities to explore the meaning of variables is insufficient to reconstruct students' schemas.

c) Misconceptions about Functions

The *"graph as picture"* misconception, that is, interpreting graphs as literal visual representations rather than mathematical representations, consistently emerged in Sajka's (2024) study, which involved 345 participants of varying proficiency levels. Eight types of this misconception were successfully identified. Ayeh (2025) also found that 11th-grade students tend to develop procedural competence rather than conceptual understanding in the topic of functions, with an overreliance on the vertical line test.

By intuitively mapping the shape of a curve to the physical path of an object, graphs are treated as images rather than representations of mathematical relationships between two variables. The absence of experience that explicitly links coordinates, rates of change, and situational context reinforces this literal interpretation. The finding that this misconception arises at various levels of proficiency confirms that routine procedures (such as memorizing graph shapes) are insufficient for building relational understanding.

d) Supporting Findings from Other Clusters

Although not the primary focus, some of the studies reviewed also support the pattern of findings. Misconceptions regarding basic numbers are found as early as preschool age (Eleftheriadi et al., 2023), with 83.3% of 8th-grade students exhibiting misconceptions about integer operations (Makonye & Fakude, 2016), confirming that a fragile early foundation has longitudinal effects. On the topics of limits and continuity, Munyaruhengeri et al. (2024) found significant misconceptions related to formal definitions, while Hendricks and Olawale (2023) demonstrated variations in probability misconceptions across grade levels. These findings are consistent with the pattern that misconceptions are cumulative and persistent.

Intervention Effectiveness: Cross-Context Comparisons

This section does not merely list the reported interventions, but synthesizes why certain interventions are effective based on the cognitive mechanisms they target.

a) Use of Digital Technology (GeoGebra & E-Learning): Reducing the Burden of Representational Mapping

GeoGebra emerges as the most frequently reported effective intervention tool. Seloane et al. (2025) demonstrate that GeoGebra is effective as a modeling tool for addressing misconceptions about complex numbers at the college level. Gregersen (2024) found that GeoGebra promotes the development of conceptual knowledge-based justifications among middle school students. Chytas et al. (2024) successfully integrated Computational Thinking through GeoGebra in calculus instruction. Haryono et al. (2024) demonstrated that collaborative e-learning successfully reduced misconceptions by 26.5%.

The dynamic representations provided by tools such as GeoGebra reduce the cognitive load of mapping between representations through immediate temporal–visual feedback. Parameter sliders, for example, allow students to observe that letters are not fixed objects but rather changing quantities, directly challenging the reification of symbols. In the topic of functions, dynamic manipulation allows students to see that the shape of the curve changes as the parameter changes, breaking the literal mapping "graph = image." Susanto (2023) also found that GeoGebra has proven to be the most popular and recommended software for helping students solve math problems, reported effects range from moderate to strong on conceptual understanding.

b) Inquiry-Based Learning and Cognitive Conflict: Reconstructing Schemas through Counter-Expectation Evidence

Siantuba et al. (2023) demonstrated that an inquiry-based online module specifically designed to address misconceptions in physics and mathematics resulted in greater conceptual change compared to the control group. Zeybek (2026) found that cognitive conflict is the most effective primary strategy for helping pre-service teachers identify and transform misconceptions. Uegatani et al. (2024) emphasize the importance of making students aware of their own “illusionary difficulties” through the design of an appropriate learning environment.

Conflict-based inquiry presents evidence that contradicts students’ expectations, forcing them to restructure deeply ingrained schemas. Unlike direct corrections, which tend to be ignored, cognitive conflict creates *a disequilibrium* that motivates students to actively reconstruct their understanding. Its effectiveness is particularly strong when the conflict is specifically designed for a target misconception (e.g., presenting two representations of fractions that appear different but are equivalent).

c) Bilingual and Multilingual Approaches: Bridging Linguistic and Mathematical Schemas

Schüler-Meyer et al. (2019) demonstrate that bilingual instruction (German/Turkish) is effective in building conceptual understanding of fractions among multilingual students, even without formal proficiency in their native language. This suggests that cross-linguistic strategies can serve as a crucial bridge in overcoming conceptual barriers.

Language support aligns mathematical academic terms with the linguistic schemas students already possess. In multilingual populations, failure to understand key terms (e.g., “part,” “ratio,” “change”) contributes to misinterpretations of instruction that are subsequently internalized as misconceptions. A bilingual approach breaks this chain by providing a cross-linguistic semantic bridge.

d) Scaffolding and Structured Interventions: A Gradual Transition from Procedures to Relationships

Gabler and Ufer (2021) demonstrate that a macro-scaffolding intervention program successfully developed problem-solving flexibility in second-grade elementary school students. Leuenberger et al. (2024) found that combining cooperative learning with individual support yielded the greatest improvement in computational competence among first-grade elementary school students, particularly for low-performing students.

Scaffolding provides a step-by-step task pathway that guides the transition from procedural mastery to relational understanding. By sequencing activities from concrete to abstract, scaffolding prevents overly large cognitive leaps, leaps that often serve as the starting point for the formation of misconceptions.

e) Teacher Training Based on Diagnostic Awareness: Strengthening Early Identification Skills

Wildgans-Lang et al. (2020) developed a computer simulation environment to train prospective teachers in diagnosing students' competencies and misconceptions. Zeybek (2026), through a 14-week teaching experiment, found that micro-teaching combined with peer evaluation effectively develops prospective teachers' readiness to address misconceptions. Copur-Gencturk emphasizes the importance of improving teachers' conceptual understanding, particularly regarding fractional operations.

Teachers who are unaware of their own misconceptions or unable to accurately diagnose students' misconceptions risk reinforcing, rather than correcting, those misconceptions. Simulation-based diagnostic training allows teachers to practice in a safe environment before facing a real classroom.

f) Questioning Strategies and Play-Based Approaches

Zhang et al. (2025) found that kindergarten teachers' questioning strategies within the Conceptual PlayWorld approach effectively facilitated the learning of mathematical concepts and spatial reasoning in children aged 5–6 years. This approach emphasizes the importance of linguistic mediation and dialogic interaction in preventing misconceptions early on.

Although this study focuses on early childhood education, the underlying principle, that guided questions that encourage students to articulate their understanding are more effective than direct correction, applies to all educational levels and reinforces findings regarding cognitive conflict.

Synthesis of Findings

The findings confirm that misconceptions are not random errors but active constructs students build from their own experiences, a view supported by their persistence even among high-proficiency learners (Potvin & Cyr, 2017) indicating that scientific knowledge and misconceptions can coexist within the same cognitive structure and that correction requires building a stronger alternative knowledge pathway rather than erasing prior beliefs.

Across the three clusters, misconceptions share a common mechanism rooted in over-reliance on a single representation and limited opportunities to explore relationships between representations, and the interventions found effective, dynamic visualization, cognitive conflict, language bridges, and gradual scaffolding, consistently work by confronting students with the limitations of such single representations. However, intervention effectiveness is highly context-dependent, hinging on grade level, specific mathematics topic, students' linguistic and cultural background, and teachers' diagnostic readiness, suggesting that no single strategy is universally applicable and that a layered, context-specific combination of approaches yields the best results.

These conclusions should nonetheless be interpreted in light of several limitations: heterogeneity in effect sizes and implementation fidelity reporting across studies constrains precise quantitative comparison, limited long-term follow-up data leave the durability of intervention effects unconfirmed, the restriction to English-language open-access articles may exclude relevant findings published in other languages, and generalizations across national curricula should therefore be made with caution.

CONCLUSION

This study concludes that misconceptions across the three clusters (fractions, algebraic variables, and functions) stem from over-reliance on a single representation, reification of symbols, and literal graph reading, patterns that are cumulative across educational levels and reinforced by the lack of explicit bridges between representations. These misconceptions are not random errors but active constructs students build from their own experiences, meaning correction requires building a stronger alternative understanding rather than mere erasure. Interventions such as dynamic tools (GeoGebra), cognitive conflict, bilingual approaches, and structured scaffolding are proven effective in addressing these patterns: GeoGebra reduces cognitive load in mapping between representations and directly challenges symbol reification and literal graph reading; cognitive conflict forces active schema restructuring by presenting evidence that contradicts students' expectations; bilingual approaches support linguistically diverse classrooms; and scaffolding aids the gradual shift from procedural to relational understanding, particularly at early grade levels. However, no single intervention is universally applicable, as effectiveness depends on grade level, topic, linguistic and cultural background, and teachers' diagnostic readiness.

Based on these findings, this study recommends that mathematics teachers adopt a staged approach, beginning with diagnosis, followed by cognitive conflict, dynamic representation, and language support, starting with the misconception cluster most relevant to their classrooms. Curriculum designers and teacher professional development programs should also give greater attention to the causal mechanisms underlying misconceptions rather than focusing solely on their types. This study is limited by the heterogeneity of effect sizes and implementation fidelity across the reviewed studies, which restricts precise quantitative comparison, as well as its focus on English-language open-access articles, which may exclude relevant findings published in other languages. Future research, particularly through meta-analysis, is needed to provide a deeper, quantitative synthesis of intervention effectiveness across the three misconception clusters.

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