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RECEIVED 20 October 2025

REVISED 13 April 2026

ACCEPTED 29 April 2026

PUBLISHED 20 May 2026

CITATION

Tripo J and Debreñti E (2026)
Mathematical development through
non-digital instruction: a meta-analysis
of primary and middle school education.
Front. Educ. 11:1729068.
doi: 10.3389/feduc.2026.1729068

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Mathematical development through non-digital instruction: a meta-analysis of primary and middle school education

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This meta-analysis explores the impact of non-digital tools and games on the development of mathematical thinking and problem-solving skills among elementary and middle school students. Through a systematic literature review, studies were selected that specifically evaluated physical instructional aids – such as board games, manipulatives, and puzzles- designed to foster cognitive engagement with mathematical concepts. The primary aim of the analysis was to assess how these tools influence students' ability to reason through problems and apply logical thinking in mathematics. Findings reveal that non-digital interventions with physical activity positively contribute to students' problem-solving abilities, particularly when used consistently and integrated into classroom instruction. The result support incorporating non-digital methods into mathematics education as effective complements to traditional approaches. These tools not only boost engagement but also help build foundational skills in analytical thinking.

KEYWORDS

early childhood mathematics, game-based learning, mathematical skills development, mathematics education, mathematical manipulatives, meta-analysis, non-digital mathematical games

1 Introduction

The fundamental idea behind cognitive development theories is that a child's thinking is not static; rather, it continuously evolves and expands as they gain new information, moving towards higher levels of organization. This process is linked to both biological maturation and the learning experiences that allow children to actively process stimuli from their environment (Türkoğlu, 2019). During childhood development, cognitive structures evolve from simpler schemes to more complex systems, integrating elements of information processing gradually. Each new learning experience can either be incorporated into an existing cognitive network or significantly transform it. Educational tools can activate multiple senses; for example, when a child solves a mathematical problem by manipulating objects, they can experience visual and tactile stimuli, which help form new mental models when combined (Liang et al., 2019). When this engagement is coupled with a structured set of exercises, the likelihood increases that a child's existing low-level schemas will gradually evolve into more complex thinking patterns.

Piaget's concept of adaptation further supports this notion: through the processes of accommodation and assimilation, the cognitive system flexibly adjusts to new experiences.

Among the pedagogical methods that encourage cognitive development, game-based interventions can be particularly effective, provided they are tailored to the child's age and prior knowledge (Celik, 2020).

Motivation directly impacts attention, which in turn influences the accuracy of information processing. Learning materials that stimulate engaging and voluntary participation are more likely to be effectively integrated into long-term memory. Research indicates that traditional playful activities, such as board games or tools requiring physical manipulation, can significantly enhance specific cognitive skills (Talan et al., 2020). These activities often help improve analysis and synthesis skills. For instance, tasks related to geometric transformations may require identifying coordinate points for simpler questions, while more complex combinations necessitate higher-level problem-solving abilities (Hamden Hamid et al., 2022). Developing these skills can enhance a student's ability to manage abstract rule sets and think rationally about hypothetical situations. From a constructivist perspective, meaningful learning occurs when students actively engage in their own knowledge construction process. Additionally, social cognitive theory suggests that interactions with others, such as cooperative play, can further reinforce this learning (Talan et al., 2020).

Examples of realistic mathematics teaching methods (RME) demonstrate that problem-solving in real-life contexts can enhance logical and creative thinking (Laurens et al., 2018). In this approach, students not only execute algorithms mechanically but also contemplate their decisions, compare real-world scenarios, and evaluate the outcomes. However, it is important to recognize that playful learning experiences can affect different students in various ways. Some children may find object-based games inspiring, while others may prefer traditional hands-on methods (Yusof and Shahril, 2021). It is the teacher's responsibility to strike a balance that ensures all student groups receive stimuli conducive to cognitive development.

Mathematical manipulatives are tools used in mathematics education that students physically handle to explore, understand, or investigate mathematical ideas and to support problem-solving through sensory experience. Concrete manipulatives are physical objects that students can directly touch and manipulate, providing rich and varied sensory input for learning mathematical concepts. Historic-cultural manipulatives are concrete mathematical artifacts developed throughout history to explore or solve specific problems, whether originating within mathematics or from broader cultural practices (Bartolini and Martignone, 2020). Together, these three categories are referred to as traditional manipulatives.

Traditional manipulatives encompass a wide range of objects that assist students in understanding mathematical concepts and operations through physical interaction. Typically made from tangible materials, these tools are specifically designed to teach particular mathematical topics. One of the most popular forms of manipulatives is board games, where both the playing field and the rule system facilitate the practice of operational skills and logical reasoning. Interventions based on board games often target numerical thinking and strategic planning simultaneously, allowing participants to calculate their moves in advance based on anticipated reactions from opponents.

Card games also play a significant role by encouraging students to quickly process information, match, or arrange elements according to specific rules. These games are especially effective for deepening number concepts or practicing concepts related to fractions. Activities involving tangrams or origami can enhance spatial visualization and understanding of geometric transformations. In these tasks, how a student breaks down a complex shape into smaller components and then reorganizes them for a specific purpose is crucial. This process of problem segmentation and reconstruction implicitly cultivates the necessary reasoning skills for geometric proofs.

Additionally, it's important to mention manipulative tools used in a sports or movement-based environment. For instance, the Eduball (Cichy et al., 2020) concept incorporates balls marked with various numbers, operation signs, or quantitative figures, prompting participants to perform calculation tasks while being active.

2 Benefits of games in mathematics teaching and learning

Astuti et al. (2025) found that mathematics serves as a fundamental pillar in the development of children's cognitive abilities, particularly in areas such as pattern recognition, understanding shapes and sizes, number concepts, and logical reasoning skills.

Games offer a natural and effective way to engage students with educational content and have been successfully employed to teach mathematical concepts. They are versatile tools that can be adapted for various age groups and skill levels. A growing body of research highlights their value as powerful educational resources (Smith, 2020). Hinebaugh (2009) highlighted particular board games and detailed the mathematical learning opportunities each offers. Classic games like *Chess* and *Checkers* have been integrated into the curricula of some school systems. Incorporating these games has helped students develop critical thinking and problem-solving skills, while also contributing to improved scores on standardized math and science tests (Debrenti, 2025; Hinebaugh, 2009).

According to Heshmati et al. (2018) games can be adapted to meet students' individual learning needs. They can be used to reinforce familiar procedures, introduce new mathematical concepts, or serve as tools for assessing students' knowledge and understanding (Wood, 1993). Through mathematical games, students are encouraged to reflect on their own comprehension, recognize their strengths and weaknesses, and learn by observing how others approach the same problems (Shaftef et al., 2005). Additionally, games can enhance social skills by teaching students to take turns, support one another, engage in positive interactions, build self-esteem and leadership abilities, and handle both winning and losing with grace (Blum and Yocom, 1996; Shaftef et al., 2005).

Lehtinen et al. (2015) found that empirically tested game-based learning environments aimed at developing complex mathematical skills and knowledge in primary education are still relatively rare. The Number Navigation Game developed by them represents the first game-based learning environment specifically designed to enhance adaptive arithmetic knowledge

and skills—areas that have traditionally been challenging to support through conventional classroom instruction. Pilot testing of the NNG game revealed that during one hour of gameplay, primary students performed approximately 180 calculations and engaged with a wide range of number combinations (Brezovszky et al., 2013). They also emphasize the importance of an iterative design process in the development of educational games, guided by key principles such as the integration of educational content with game mechanics, the inclusion of assessment components, and the application of learned skills through practice

Bragg (2012) investigated students' on-task behavior during mathematics lessons involving non-digital games in comparison to traditional, non-game-based lessons. Her study revealed that students were on task for 93% of the time during game-based lessons, whereas this figure dropped to 72% in non-game-based lessons. These findings suggest that incorporating games into mathematics instruction can significantly enhance students' time-on-task. Specifically, using games that directly align with the mathematical content being taught may increase student engagement and thereby improve learning outcomes. Debrenti and Bella (2025) in their qualitative research action introduced the Poly-Universe game family to students in grades I to VI, mathematically gifted high school students, and primary teachers. They found that the Poly-Universe kit could be effectively integrated into personal development, language, math, and art classes

Russo et al. (2024) present an analysis and synthesis of 34 studies and found that mathematical games generally had a positive impact across a wide range of outcomes. This indicates that mathematical games can serve as effective tools for developing mathematical skills and strengthening positive attitudes toward mathematics.

3 Games in research

Moyer (2001) found that while meta-analyses and research reviews have documented the use of manipulatives in structured mathematics settings, there is a noticeable gap in the literature regarding how teachers use manipulatives in everyday classroom contexts for their own instructional purposes. Teachers play a vital role in shaping mathematical learning environments that offer students meaningful representations to support their thinking. However, even when teachers are trained in effective manipulative use, their underlying beliefs about how students learn mathematics can strongly influence both the manner and the purpose of their implementation. It is essential that teachers critically reflect on students' mathematical representations and guide them toward more advanced, abstract understanding. This study uses observations, interviews, and self-reported data to explore the ways in which teachers utilize manipulatives and the reasoning behind their instructional choices

Russo et al. (2021) investigated related games usage in primary schools. About total of 248 Australian primary school teachers completed a questionnaire exploring their use of mathematical games in the classroom. The survey examined their motivations for using games, how often they incorporated them, how games fit within their lesson structures, and their perceptions of games'

effectiveness in achieving educational goals. Nearly all respondents reported using math games at least once a week. These games served various instructional purposes, including warm-up activities, introducing new concepts, reinforcing skills and knowledge, and supporting fluency practice. Aligning with previous studies, teachers generally regarded games as a highly effective tool for engaging students in mathematics. Their findings indicate that educators' perceptions of a game's educational value are strongly influenced by how challenging, engaging, and enjoyable they find the game, as well as its adaptability to accommodate diverse learners and its potential to be transformed into a broader mathematical investigation. Likewise, teachers' likelihood of using a game with their students in the future depends largely on their perceptions of student enjoyment, engagement, and the game's ability to facilitate deep mathematical exploration. Additionally, the game's capacity to foster mathematical discussions was also a key factor in its perceived usefulness (Russo et al., 2023).

Foulkes (2025) also observed that practitioners employed a variety of manipulatives to support mathematics learning, including some with complex or potentially distracting features. Children's perceptions of manipulatives were influenced by the way they were introduced; when the initial approach highlighted the mathematical properties of the materials, children were more likely to view them as "tools for maths". Jaramillo et al. (2025) conducted a bibliometric analysis using the Scopus database, examining research on mathematical games for learning mathematics from 2000 to 2024. Their findings indicate that the field has evolved significantly, with increased diversity in research topics. The results highlight a growing trend in the integration of games into classroom practices, particularly through collaborative and interdisciplinary approaches, which positively influence students' attitudes and behaviors toward mathematics.

The literature reveals a contrast between teachers' preference for using non-digital games with students and the research tendency to emphasize digital games. Most studies on game-based learning in mathematics specifically focus on digital rather than non-digital games (Debrenti, 2024).

4 Method

Our research was based on a meta-analysis calculation, which followed a systematic review. The criteria established for including and excluding studies were as follows:

- Inclusion criteria: (1) studies that do not use digital objects during the intervention, employing traditional tools (e.g., board games, chopsticks, cards, etc.); (2) studies that develop mathematical thinking and/or focus on specific areas of mathematics; (3) studies published in English; (4) no limitations regarding the countries or the duration of the intervention; (5) studies that reported pre-test and post-test results; (6) Availability of necessary data for the meta-analysis (sample sizes, means, standard deviations, *t*-test values, *F*-test values); (7) Studies that included separate intervention and control groups.

- Exclusion criteria: (1) studies that only involve “question chains”, “inquiry-based learning”, etc.; (2) studies that do not specify a particular tool; (3) studies that employ digital tools in the intervention; (4) studies comparing traditional and digital tools; (5) studies published before 1990. (6) studies not published in a peer-reviewed scientific journal; (7) studies lacking a control group.

The search for studies to include in the meta-analysis was conducted in July 2025 using the ProQuest and Google Scholar databases. The following keywords were used: (mathematical game OR mathematical games OR mathematics game OR mathematics games) AND (primary school OR elementary school OR primary OR elementary OR middle school OR middle) AND (board OR card OR strategic OR logical OR verbal) AND (non-digital OR traditional) AND (student* OR teacher*) NOT (digital OR virtual OR virtual world OR mobile OR software OR computer* OR technol* OR console* OR preschool OR pre-school OR kindergarten OR prep*).

During data processing, we utilised Microsoft 365 Excel, Zotero, and Meta-Essentials 1.5 (Hak et al., 2016; Suurmond et al., 2017; Van Rhee et al., 2015). In our systematic search, we adhered to the PRISMA 2020 guidelines.

As an initial step of the meta-analysis, the pooled standard deviation and Cohen’s d (1988) effect sizes were calculated:

$$d_s = \frac{\bar{x}_A - \bar{x}_B}{s_{pooled}}$$

The formula for the pooled standard deviation:

$$s_{pooled} = \sqrt{\frac{(n_A - 1)s_A^2 + (n_B - 1)s_B^2}{n_A + n_B - 2}}$$

where s_A^2 and s_B^2 are standard deviation of the two groups, $\bar{x}_A$, n_A are the mean and the number of elements of the intervention group, and $\bar{x}_B$, n_B are the mean and the number of elements of the control group. In two cases, instead of the standard deviation of the groups, the t -value was given, in which case the Cohen effect size value (Cohen, 1988) is equal to:

$$d_s = t \cdot \sqrt{\frac{n_A + n_B}{n_A \cdot n_B}}$$

We calculated the Hedges effect size, which is based on the Cohen effect size, supplemented with a correction index (J):

$$J = 1 - \frac{3}{4 \cdot df - 1}$$

where $df = n_A + n_B - 2$. So the value of the Hedges effect size, which we denote by g (Anggoro et al., 2025):

$$g = J \cdot d_s$$

Subsequently, the combined effect was estimated, tests for heterogeneity were performed, and potential publication bias was examined.

5 Results

During the systematic literature review, a total of 2,209 studies were identified from the Proquest (1,547 studies) and Google Scholar (662 studies) databases. Additionally, 12 studies were found through the references of other articles. After reviewing the full texts, 16 out of 165 studies met the inclusion criteria (see Figure 1).

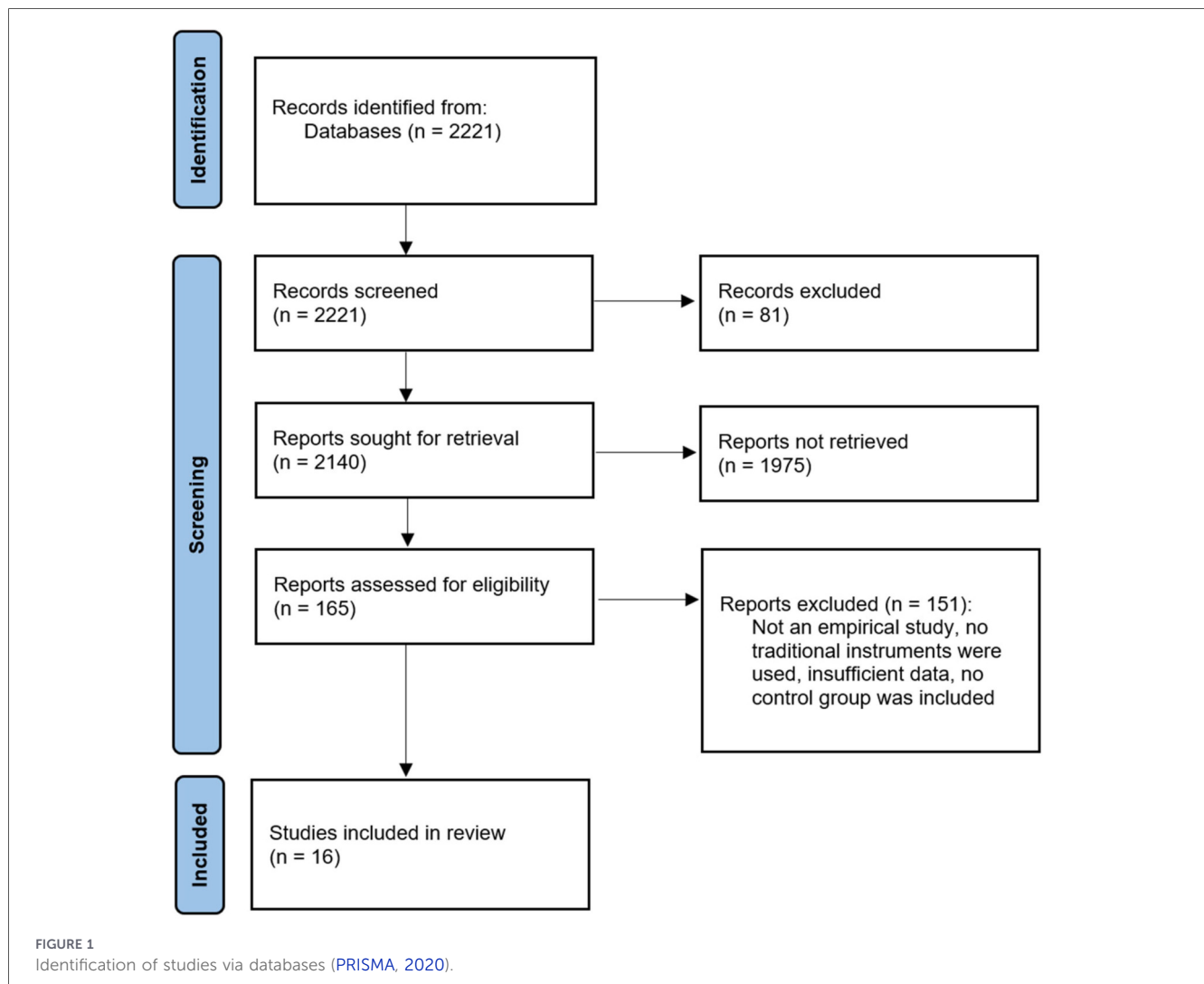
During the systematic review, it was identified that the studies by Türkoğlu (2019) and Yusof and Shahrill (2021) each reported two separate experiments, therefore, these studies were included twice in the meta-analysis. A detailed overview of all included studies is presented in Table 1.

To calculate the effect sizes for each study, we required the means, standard deviations, and the number of students measured in both the intervention and control groups for each session, as well as the t -values and F -test values. The qualitative classification of effect sizes is as follows: 0–0.2 indicates a weak effect, 0.21–0.5 indicates a modest effect, 0.51–1 indicates a moderate effect, and above 1 indicates a strong effect (Suparman et al., 2021).

A random-effects model was utilized to calculate the combined effect, as the conditions for a fixed-effects model are rarely met in educational research analyses (Van Rhee et al., 2015). In a random-effects model, we assume that the distribution of the “true” effects underlying each study has an unknown standard deviation, which means that both the mean and the variance between the studies must be estimated. In Meta-Essentials, the random-effects model is set as the default option.

The individual effect sizes (Hedges’ g) ranged from 0.37 to 2.43, indicating substantial variability across studies (Table 2). Most interventions produced medium to large effects, consistent with previous research showing that game-based learning can meaningfully enhance students’ cognitive and motivational outcomes (Clark et al., 2016; Sailer and Homner, 2020). The highest effect size was observed in Mohammed (2020) ($g = 2.43$), suggesting that certain types of active, movement-based mathematical games may exert particularly strong impacts on early learners. Conversely, smaller effects (e.g., Vogt et al., 2018: $g = 0.37$) may reflect differences in intervention duration, instructional alignment, or learner characteristics.

The random-effects model yielded a combined effect size of Hedges’ $g = 0.97$, with a 95% confidence interval ranging from 0.62 to 1.31. According to Cohen’s (1988) conventions, this represents a large overall effect, indicating that game-based learning interventions substantially improve mathematics achievement on average. This combined effect exceeds the magnitude reported in several earlier meta-analyses (e.g., Tokac et al., 2019; Wouters et al., 2013), suggesting that the studies included in the present analysis may involve more targeted, structured, or developmentally appropriate game-based approaches. However, the heterogeneity statistics indicate that the magnitude of the effect varies considerably across studies. The Q statistics were significant ($Q = 83.6$, $p < .001$), and the I^2 value of 79.7% indicates substantial heterogeneity (Higgins and Thompson, 2002). This suggests that the combined effect size should be interpreted with caution, as the true effects differ across populations, game types, and instructional contexts. The



prediction interval (-0.04 – 1.98) further supports this interpretation: although future studies are likely to find positive effects, the magnitude may vary widely.

The Z-value is 5.92 ($p < .001$). Therefore, we can reject the null hypothesis that there is no significant effect and accept the alternative hypothesis. This suggests that the use of traditional manipulatives significantly enhances mathematical skills in primary and middle school students.

Rosenthal's Failsafe-N number indicates how many additional publications are required for the overall effect size to lose its significance. In this instance, $1,522$ and $1,706$, new studies with non-significant results (i.e., small effect sizes) would need to be published for the combined effect of the studies included thus far to become insignificant. Fisher's failsafe number employs the natural logarithm of the p -values from the studies included in the meta-analysis. It then uses a Chi-square test to evaluate the stability of the results of the meta-analysis. However, Orwin's failsafe N (0) highlights that publication bias cannot be entirely ruled out, consistent with Rothstein et al. (2005), who caution against relying on a single indicator.

Overall, the results demonstrate that game-based learning has a consistently positive and often substantial impact on mathematics achievement, but the variability across studies

underscores the importance of examining moderating factors such as age, country, and duration of intervention.

The studies can also be categorized into subgroups based on various criteria, as shown in Table 3. These categories include the geographical location of the intervention. Twelve publications originated from Asia (specifically: Indonesia, Turkey, Malaysia, China, Taiwan, Palestine, and the Kingdom of Saudi Arabia, Brunei), five from Europe (Poland, Romania, and Switzerland), and one from the United States (California). According to the Hedges' g effect size, a strong effect is observed in the Asia group, and a medium effect in the Europe and USA groups. The combined effect size in the grouping by country is 0.84 (CI: -1.27 – 2.95).

In a random-effects model, differences between subgroups are indicated by the value and significance of Q_{between} . It is important to note that in this context the Q statistics does not test heterogeneity – that is, it does not assess whether studies within subgroups are homogeneous (Van Rhee et al., 2015). Instead, it reflects the decomposition of variance, showing whether differences exist between subgroups. For the subgrouping by country, the result $Q_{\text{between}} = 3.77$, $p = 0.052$ suggests that there is a difference between the subgroups when adopting a 10% significance level. This implies that the geopolitical location of

TABLE 1 Summary of the studies included in the meta-analysis.

St. Nr.	Study name	Country	Grade	Kinds of games	N	s_pooled	Cohens's d
1	Andayani et al. (2022)	Indonesia	3rd grade	Environmental-Based GESAMSU (Gedrik Saruk Indeed Seru) game	62	26,715	0.948
2	Türkoğlu (2019), A	Turkey	2nd grade	Board game based cognitive trainings	60	5,167	0.710
3	Türkoğlu (2019), B	Turkey	3rd grade	Board game based cognitive trainings	60	4,979	0.609
4	Celik (2020)	Turkey	3rd grade	Cube rolling game, “symmetry Game”	58	2,444	0.855
5	Cichy et al. (2020)	Poland	1st grade	Eduball (physical exercise class)	47	7,412	0.492
6	Debrenti and Laszló (2020)	Romania	2nd grade	Card games	30		
7	Debrenti (2025)	Romania	4th grade	Textbooks, workbooks, chess	30	17,899	1.002
8	Debrenti (2017)	Romania	3rd–4th grade	Simple word problem, logical games	32	27,448	0.919
9	Hamden Hamid et al. (2022)	Malaysia	14 years old	Transformation Checkers (TC) game and Worksheets	116	4,813	0.391
10	Kamii et al. (2005)	California	1st grade	Pick-Up Sticks, bowling, Balancing Cubes, Piggy Bank (card game)	46	24,612	0.760
11	Laurens et al. (2018)	Indonesia	junior high school	Snake and ladder, Realistic Mathematics Education (RME)	50		
12	Liang et al. (2019)	China	5 years old	Rtl-based mathematical game, card game	63	4,838	0.529
13	Lin and Cheng (2022)	Taiwan	6th grade	40 RFID cards	22	21,623	0.967
14	Mohammed (2020)	Kingdom of Saudi Arabia	1st grade	Active recreational maths games (AMRG)	60	4,480	2.462
15	Murtagh et al. (2022)	Palestine	1st–4th grade	Guided play and games	859	22,581	0.651
16	Vogt et al. (2018)	Switzerland	5–6 years old	Card and board games	218	17,848	0.373
17	Yusof and Shahrill (2021), A	Brunei	9th grade	Break the Code, card game	30	2,124	1.601
18	Yusof and Shahrill (2021), B	Brunei	9th grade	Break the Code, card game	40	2,366	1.353

the intervention influences the applicability of non-digital tools in mathematics lessons. Geographical location accounts for approximately 14% of the total variance (Pseudo $R^2 = 13.78\%$).

We also divided the selected studies into three groups based on the duration of the intervention. The first group consisted of studies where the intervention lasted less than two months (six studies). The second group included interventions that lasted more than two months (five studies). The third group comprised studies that specified the duration of each session (e.g., 15–20 min) but did not provide a description of the overall intervention duration. In the subgroup analysis based on the duration of the intervention, no significant differences were found in effect sizes, as indicated by $Q_{\text{between}} = 1.74$, $p = 0.419$. Thus, the length of the intervention did not substantially influence the effectiveness of the examined interventions, suggesting that the use of non-digital games can be effective even over a short period. Duration, as a moderator, appears to be a weak explanatory factor, accounting for only about 8% of the variance (Pseudo $R^2 = 7.89\%$).

For age categorization, we used the ninth year of life and the third grade as the cutoff points. Consequently, twelve studies were included in one subgroup, while six studies were included in the other subgroup. In the age-based subgroup analysis, the Hedge's g value of 0.81 for children under nine years indicates a medium effect, whereas the value of 1.37 for children above nine years reflects a strong effect. However, no significant differences in effect sizes were detected between the age groups,

as indicated by $Q_{\text{between}} = 1.86$, $p = 0.172$. This suggests that the use of non-digital mathematical games is effective in both primary and secondary school contexts. At the same time, age appears to be a weak moderator, explaining only about 8% of the variance (Pseudo $R^2 = 8\%$).

6 Discussion

The findings of this meta-analysis provide compelling evidence that the use of traditional, non-digital mathematical tools and games has a substantial positive impact on children's mathematical development. While previous meta-analyses have primarily focused on digital games (Clark et al., 2016), gamification (Sailer and Homner, 2020), or general game-based learning across subjects (Wouters et al., 2013), the present study differs in a crucial way: it concentrates specifically on non-digital, hands-on mathematical tools and games, and it examines their effectiveness predominantly in early and middle childhood. This focus fills an important gap in literature, as young learners' mathematical development is strongly influenced by concrete, manipulable experiences that supports the transition from intuitive to formal reasoning (Sarama and Clements, 2009).

The use of traditional, non-digital manipulative tools in developing mathematical thinking has a positive impact on several levels, particularly regarding students' motivation,

TABLE 2 The overall effect size of each study.

St. Nr.	Study name	Hedges' g	CI lower limit	CI upper limit	Weight
1	Andayani et al. (2022)	0.94	0.42	1.48	5.89%
2	Türkoğlu (2019), A	0.70	0.18	1.24	5.93%
3	Türkoğlu (2019), B	0.60	0.09	1.13	5.97%
4	Celik (2020)	0.84	0.30	1.41	5.64%
5	Cichy et al. (2020)	0.48	−0.10	1.08	5.40%
6	Debreñti and Laszló (2020)	1.23	0.47	2.06	3.95%
7	Debreñti (2025)	0.97	0.22	1.78	4.07%
8	Debreñti (2017)	0.90	0.16	1.68	4.16%
9	Hamden Hamid et al. (2022)	0.39	0.02	0.76	7.49%
10	Kamii et al. (2005)	0.75	0.15	1.37	5.22%
11	Laurens et al. (2018)	0.40	−0.16	0.97	5.59%
12	Liang et al. (2019)	0.52	0.02	1.04	6.11%
13	Lin and Cheng (2022)	0.93	0.06	1.87	3.44%
14	Mohammed (2020)	2.43	1.78	3.14	4.65%
15	Murtagh et al. (2022)	0.65	0.51	0.79	9.71%
16	Vogt et al. (2018)	0.37	0.10	0.64	8.51%
17	Yusof and Shahrill (2021), A	1.56	0.76	2.44	3.72%
18	Yusof and Shahrill (2021), B	1.33	0.66	2.05	4.57%

cognitive engagement, and experiential learning processes. Utilizing physical objects allows students to interact with the material through multiple sensory channels, which enhances their understanding and promotes long-term knowledge retention. These tools provide a tangible focus, especially in areas that require visual-spatial thinking, such as geometric transformations or the grasping of abstract concepts.

Game-based learning means the use of games for educative purposes and aimed at improving the user knowledge and experience. The main benefit of these educational games is they focus on improving children's life-essential abilities such as problem solving and critical thinking. GBL aimed to improve the user's knowledge and experience.

It is essential to distinguish between tools and games; not all playful elements qualify as mathematical games. Non-digital

mathematical games are understood as activities designed to achieve specific mathematical learning goals. This differs from educational gamification, where the classroom environment itself is transformed into a playing field.

The results demonstrate a large combined effect size ($g = 0.97$), indicating that traditional mathematical tools – such as board games, card games, manipulatives, and structured play activities – significantly enhance children's mathematical performance. This aligns with developmental theories suggesting that early mathematical thinking is grounded in sensorimotor and visual-spatial experiences (Mix et al., 2016). Unlike digital environments, which often rely on symbolic or screen-based representations, physical tools allow children to manipulate objects, observe transformations, and externalize their reasoning processes. These embodied interactions may explain why several

TABLE 3 The results of study characteristic analysis.

Study Characteristics	Group	Studies Number	Hedge's g	CI lower limit	CI Upper limit	Q_{between}	P_Q
Publication's country	Asia	12	1.1	0.64	1.57	3.77	0.052
	Europe + USA	6	0.66	0.4	0.92		
Duration of intervention	Less than 2 months	6	0.75	0.5	1.01	1.74	0.419
	More than 2 months	5	0.93	0.26	1.6		
	Not specified	7	1.18	0.47	1.89		
Students years	<9 years old students (<3rd grade)	12	0.81	0.52	1.09	1.86	0.172
	>9 years old students (>3rd grade)	6	1.37	0.57	2.16		

studies in the dataset, particularly those involving younger learners, produced strong effect sizes.

A key contribution of this study is its emphasis on age as a moderating factor. The subgroup analyses revealed that interventions targeting children under nine years old produced effects comparable in magnitude to those observed among older learners. This finding aligns with prior research showing that early mathematical skills are strong predictors of later academic achievement (Duncan et al., 2007). Synthesizing results from diverse cultural and educational contexts further strengthens the argument that early, structured use of mathematical tools may help reduce performance gaps that often emerge even before school entry (Beka, 2017).

Another distinctive feature of this study is its focus on non-digital tools, which remain underrepresented in contemporary educational research dominated by digital learning technologies. While digital games have been widely studied, non-digital tools are more accessible in low-resource settings, require minimal technological infrastructure, and can be easily integrated into everyday classroom practice. The strong effects observed here suggest that such tools offer a cost-effective and pedagogically robust alternative to digital interventions, particularly in early grades where tactile engagement is developmentally appropriate.

Despite the overall positive findings, the substantial heterogeneity ($I^2 = 79.63\%$) indicates that the effectiveness of traditional mathematical tools varies across contexts. Differences in intervention duration, instructional design, cultural background, and the nature of the success of game-based learning depends on careful alignment between the game mechanics and the targeted mathematical concepts (Tokac et al., 2019). For example, games that explicitly integrate reasoning, strategy, or problem-solving tend to produce stronger effects than those emphasizing rote practice.

In summary, this meta-analysis contributes uniquely to the field by demonstrating that non-digital mathematical tools and games are highly effective in supporting early mathematical development, offering strong empirical support for their continued use in early childhood and primary education. The findings highlight the importance of hands-on, playful learning experiences and underscore the need for further research examining which specific tool characteristics and instructional conditions maximize their effectiveness. By focusing on younger learners and non-digital interventions, this study provides valuable insight for educators seeking developmentally appropriate, accessible, and evidence-based strategies to strengthen foundational mathematical skills.

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

JT: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. ED: Conceptualization, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feduc.2026.1729068/full#supplementary-material>

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