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Visuospatial and Embodied Cognition in STEM Education: A Systematic Literature Review

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Abstract

This systematic literature review explores the concept of embodied cognition, which asserts that the human mind is interconnected with the physical body, and learning occurs through direct engagements with the surrounding world. Within the fields of Science, Technology, Engineering, and Mathematics (STEM) education, embodied cognition theory has attracted growing interest as a methodology for improving learning and cultivating effective problem-solving abilities. This paper aims to provide current understanding and advancements in visuospatial skills. These skills are recognized to play a critical role in achieving and acquiring knowledge in STEM disciplines. The review used Scopus and Web of Science databases to search for high-quality papers related to spatial skills and embodied cognition. Through the utilization of the PRISMA 2020 protocol, over five thousand papers were narrowed down to 42 relevant ones that were included for further analysis. Thematic analysis was then employed to identify key themes related to embodied cognition, visuospatial skills, and STEM, which revealed that most research involving embodied cognition in STEM education was conducted at the elementary and middle school level with the greatest focus on mathematics learning. These findings indicate that visuomotor skills have a substantial impact on gaining success in mathematics, which is crucial for a foundation in engineering.

Keywords: Embodied cognition, Visual skills, Spatial skills in engineering, STEM education

I. Introduction

The integration of visuospatial and embodied cognition concepts has great potential to transform pedagogical methods in Science, Technology, Engineering, and Mathematics (STEM) education, providing opportunities to improve learners' conceptual comprehension and problem-solving abilities. As STEM research focuses more on workforce development and students' career visions rather than content learning, Takeuchi et al. [1] emphasize the need to examine current learners, target learners, and their positions with respect to STEM. They argue that improving the rate of learning transfer across STEM education requires greater focus on spatial skills as a part of STEM integration applicable and relevant to industry context. Literature suggests that visuospatial skills contribute to success in STEM disciplines [2]–[4]. Children with good visuospatial skills performed better on numeric tasks, such as estimating the values on a number line, while children with poor visuospatial skills were less accurate in their estimation [5], [6].

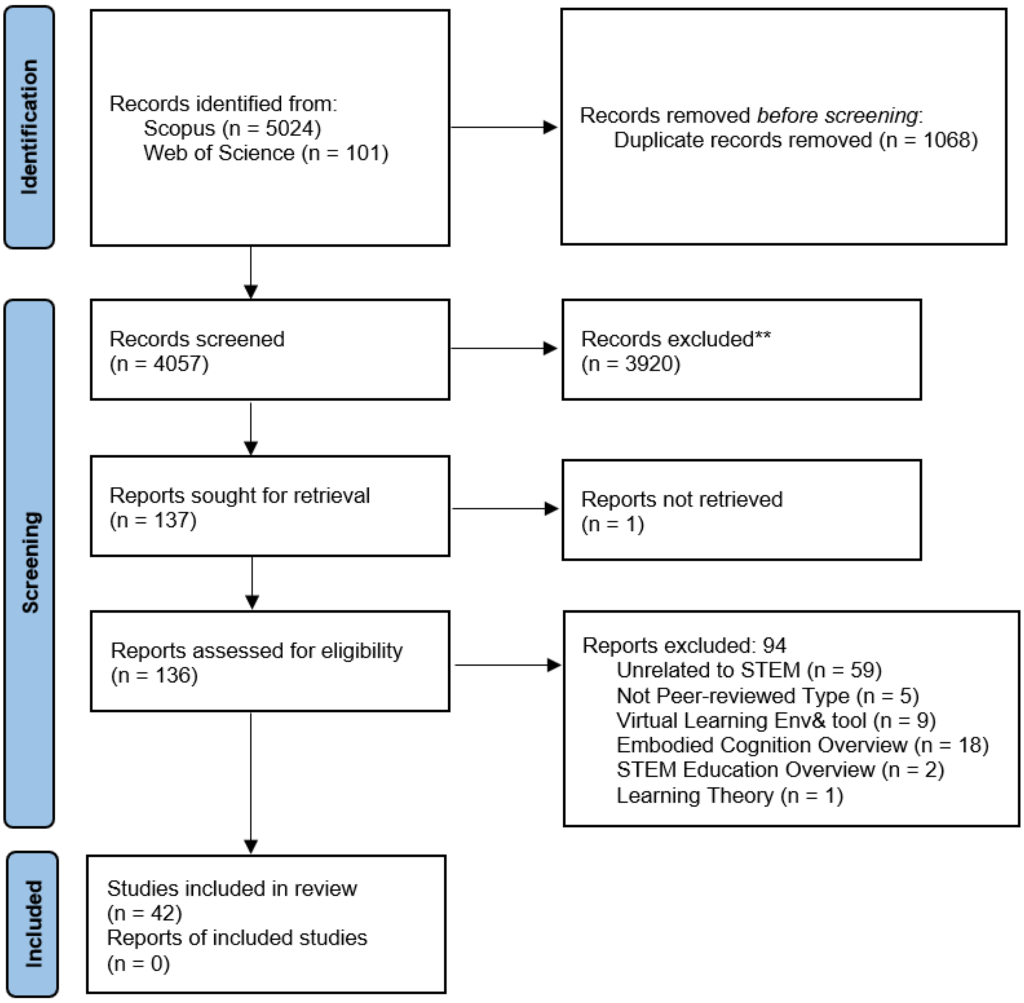
Because spatial skills are crucial for success in STEM courses and careers, scientific-based interventions should focus on embodiment, engaging the body, and actions in meaningful ways to understand field concepts [7]. These interventions should support STEM pedagogical goals, action-to-abstraction transition, and gesture support. Besides, embodiment should incorporate sensorimotor information, perception, action, embodied cognitive tools, and gestures for transforming STEM education [8]. This paper aims to provide current understanding and advancements in visuospatial skills in STEM disciplines. A considerable body of research has been conducted in exploring visual and spatial skills. However, as far as we know, no previous research has systematically investigated the development of visuospatial skills and embodied cognition in the context of STEM education. This systematic review fills a critical gap by comprehensively synthesizing current research on visuospatial skills in STEM disciplines, offering a new perspective on their development and connection to embodied cognition.

We have divided the rest of this study into the following sections to help convey our findings more clearly: Section 2 outlines the specific methodologies we employed in literature collection and analysis. Section 3 presents the results of this study. Then, we discuss the major findings in section 4, followed by the conclusion in the final section.

II. Methods

We employed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 protocol to ensure the trustworthiness of our systematic literature review (SLR) study. PRISMA 2020 is the most up-to-date version of its predecessor, PRISMA 2009, which was formulated by Moher et al. [9] and specifically aimed to be used in healthcare-related research. This methodology provides guidelines for comprehensively documenting the entire history of systematic review work, starting from the initial planning phase to the final findings [10]. The primary distinction between the two versions of PRISMA lies in the fact that the most recent one has greater adaptability to other methods from various fields [11]. Figure 1 depicts the SLR methods we performed in conducting this study. A detailed explanation of each PRISMA phase is discussed in the following subsections.

Figure 1: PRISMA Flowchart



A. Identification Phase

The objective of this preliminary phase is to figure out the number of prospective reports sought from databases. In this SLR work, we started this step by formulating a search strategy for data collection. Because the data primarily consisted of scholarly publications, a search query was devised in accordance with our study inquiry to identify the current knowledge and growth regarding visuospatial abilities within the domains of science, technology, engineering, and mathematics (STEM). We established the first search string by combining each keyword using Boolean operators as follows, "(spatial OR visual) AND (skills) AND ("embodied cognition" OR "embodied play")." The logical operator "OR" was applied to categorize comparable keywords or phrases. For example, we combined the terms "spatial" with "visual" to broaden the scope of publications pertaining to visuospatial topics. Next, we employed the "AND" operators to concatenate each set of strings. We then execute such a query across Scopus and Web of Science (WoS) databases to obtain high-quality literature. These databases offer extensive search functionalities that allow for the effective use of Boolean operators during the search procedure. Table 1 summarizes the comparison of search queries and the initial results obtained from both databases that we conducted in early October 2023.

Table 1: Results of initial search query

Search String	Databases	Results
(spatial OR visual) AND (skills) AND ("embodied cognition" OR "embodied play")	Scopus	3663
	Web of Science	93
	Total	3756

Due to a high number of initial results, we proceeded to refine the focus, as shown in Table 2, by including the term "engineering" in our search string. We also modified the string by adding the word "abilit*" followed by a wildcard operator to extract articles that include the word "ability" or "abilities," which are synonymous with the term "skill." The query returned fewer records, with Scopus decreasing over 2000 documents compared to the results obtained from the earlier search attempt. Surprisingly, when we implemented the modified query into the WoS searching box, it suppressed the results to nearly one-twelfth of the entries returned in the initial query.

Table 2: Results of search query refinement

Search String	Databases	Results
(spatial OR visual) AND (skills OR abilit*) AND ("embodied cognition" OR "embodied play") AND (engineering)	Scopus	1361
	Web of Science	8
	Total	1369

Given a broad discrepancy in the number of records yielded, we opted to investigate all records obtained from both search attempts to ensure that no relevant information was overlooked. As a result, we exported a total of 5125 records into four separate CSV files, each containing information on authors, title, publication year, abstract, and keywords. Specific to Scopus' records, we additionally included the document type attribute.

The next step involved in this identification stage is to eliminate redundant entries among the data that was collected from the preceding search procedures. To do so, we consolidated the four CSV files resulting from the search queries into two separate spreadsheets, categorized according to the database name. Besides, we assigned different colors to distinguish between records obtained from each search attempt (i.e., queries with and without engineering terminology). We then utilized the conditional formatting feature provided by Microsoft Excel by selecting the Highlight Cells Rules option, followed by clicking on the Duplicate Values function. As a result, a total of 1067 identical items were detected in the data records from Scopus, while only one duplication was located in WoS.

B. Screening Phase

Following the elimination of duplicate entries, we scrutinized the remaining 4057 records. We performed a three-stage screening process with the objective of selecting relevant literature for synthesis. During the first screening process, our attention was directed toward reviewing the titles and abstracts of the remaining entries that were pertinent to our objectives, which were to determine the existing knowledge and development of visual and spatial skills in STEM disciplines. We disregarded records that specifically address the concept of embodied cognition in topics related to the therapy of brain diseases such as Parkinson's, congenital brain lesions, and neurological disorders. Besides, entries related to developmental disorders (e.g., dyspraxia, cerebral palsy), learning disorders such as dyslexia, reading and writing disability, and nerve networks dysfunction like Attention-Deficit/Hyperactivity Disorder (ADHD) and autism were also omitted for further analysis. In addition, any items discussing the application of visuospatial skills in the acquisition of artistic, linguistic, or athletic knowledge were excluded. Further, we removed any records discussing computer interface, robotics, critical thinking, design thinking, and tourism from the list. Finally, we eliminated certain entries that were written in languages other than English. Consequently, 3920 records were excluded.

We then started the second screening process by downloading the remaining 137 entries. However, we encountered an issue where one document, which was published in 2022, could not be retrieved due to institutional subscription issues. Therefore, we moved on to the final screening stage with 136 eligible documents included for full-text screening, where we paid attention to review the characteristics of the studies by focusing on the context of studies employing embodied cognition and visuospatial skills. Specifically, we seek information on whether the studies related to the context of problem-solving, math learning, science learning, and hands-on learning. If we were unable to locate such information, the studies would be excluded. In addition, we set two supplementary restrictions in terms of year and type of publications. To acquire the most recent knowledge on the topic, papers published since 2010 were preferred. Furthermore, the included articles must be reviewed blindly to confirm the reliability of the findings. Table 3 shows the list of inclusion and exclusion criteria that we applied during the whole screening phase.

A rigorous final screening round led to the exclusion of 94 articles. 59 articles lacked a focus on STEM fields, five were non-peer-reviewed publications, nine focused on virtual learning environments, 18 provided broad overviews of embodied cognition, two addressed general STEM education, and a single article was on learning theory. Ultimately, 42 studies were selected for further analysis, comprising 31 journal articles, nine conference proceedings, and two book chapters that had passed a peer-reviewed procedure.

Table 3: Inclusion and Exclusion Criteria

Inclusion	Exclusion
- Must be written in English - Blind review papers - Related to STEM disciplines - Published since 2010	- Book - Lecture notes - Thesis or dissertation

Although we carefully followed all the phases of PRISMA 2020 and maintained exhaustive documentation, we recognized the implicit biases that may exist during the process. In the identification phase, we used systematic search strategies on Scopus and Web of Science databases. However, we observed significant differences in the number of records found, implying the presence of publication and availability biases that could potentially lead to the underrepresentation of relevant research in our final analysis. In addition, revising search queries, while intended to improve specificity, might unintentionally generate reporting bias by disregarding relevant literature that was not captured by the changed terms, which might result in an incomplete picture of the evidence. Furthermore, we applied strict criteria throughout the screening step to pick literature aligned with our research objective. Nevertheless, there is a possibility of imposing selection bias due to inclusion/exclusion criteria, particularly in constraining the selection of blind-reviewed papers. This possibly excluded valuable research provided in non-blind reviewed publications, including grey literature types (e.g., reports, theses, dissertations, white papers, etc.), which could impact the comprehensiveness of the review.

C. Analysis

We thoroughly examined the 42 eligible studies by meticulously extracting and synthesizing key information pertaining to our objectives. To facilitate data synthesis, our data extraction focused on highlighting features discussed in each study, including objectives, methods, results, limitations, and conclusion, as outlined by Petticrew and Roberts [12]. We then employed a two-pronged approach to minimize biases, utilizing both human and technological techniques with the aid of NVivo 14. The latter method facilitated a systematic and transparent approach to theme identification that enabled us to explore a wider range of potential themes, leading to a more comprehensive understanding of the data and novel insights into this study.

We used thematic analysis to discover and investigate themes related to the ideas of embodied cognition, visuospatial skills, and STEM. Our consensus of the themes identified through both manual and electronic processes was achieved through a transparent and constructive discussion, where each reviewer provided additional details of information in order to refine the coding criteria.

III. Results

This section summarizes the main findings made during our analysis. We commence with statistical data describing the characteristics of the references selected in our review, including the year of publication, the type of articles (i.e., journal paper, conference proceeding, book chapter), and research categories (i.e., empirical study, literature study). Then, we outline the primary themes revealed in the next parts of this section. Appendix A provides a concise overview of the papers selected for this study.

Figure 2: The distribution of the included studies

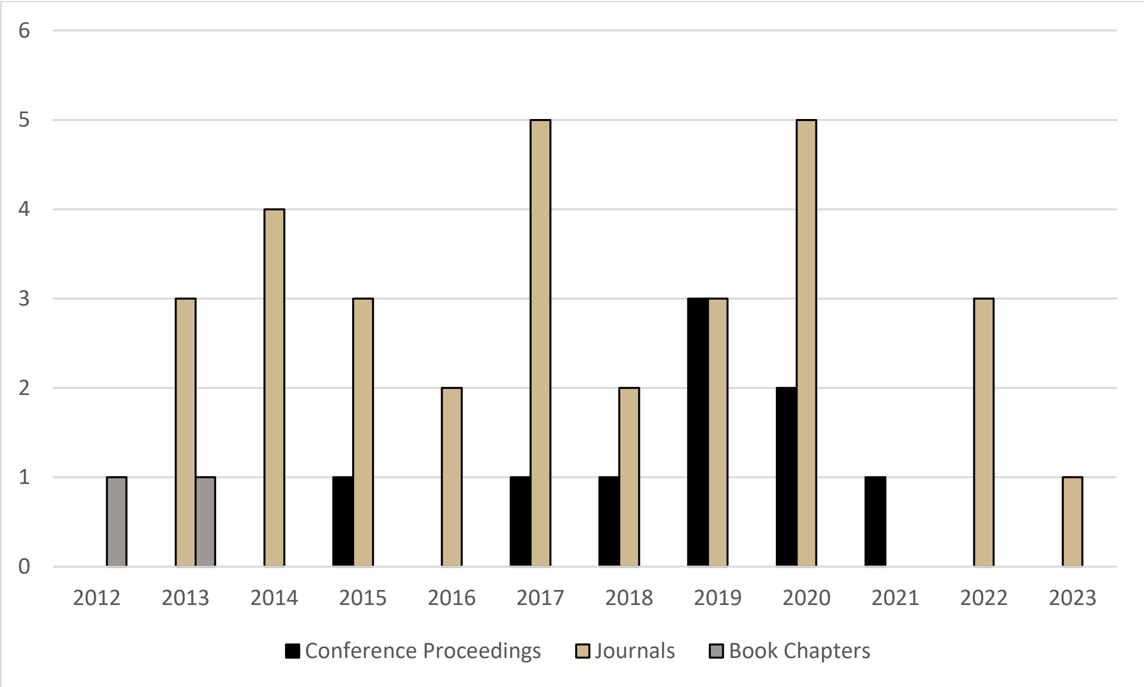
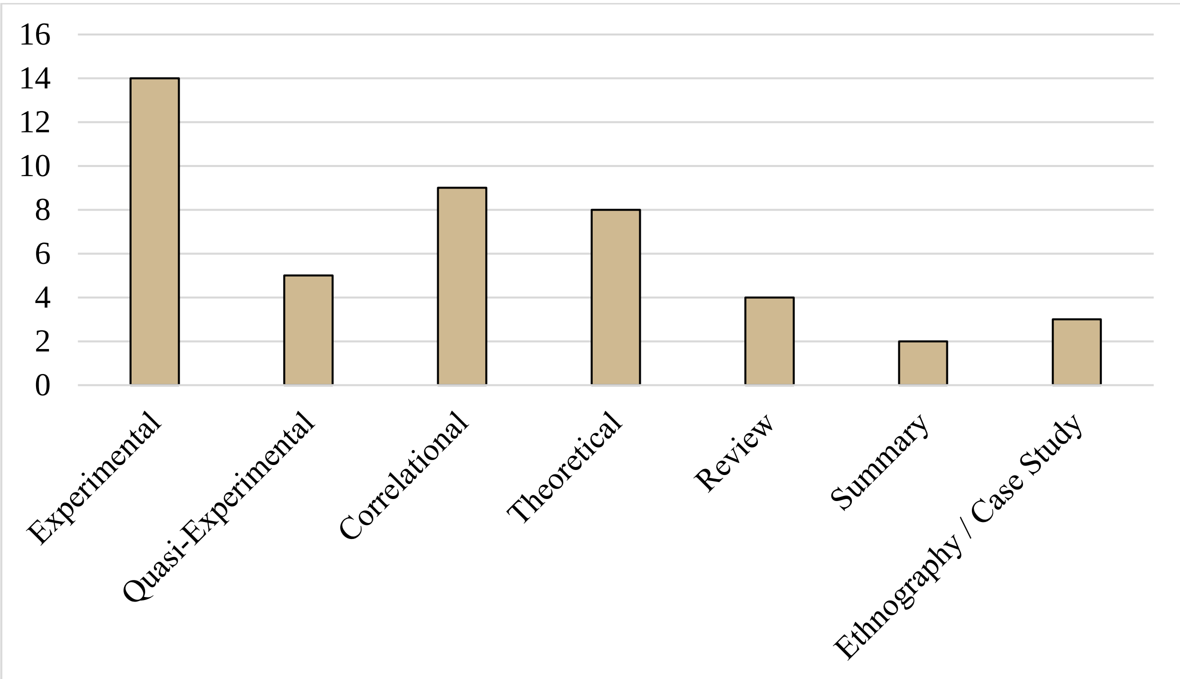


Figure 2 provides a concise overview of the acquired publications, adhering to the PRISMA 2020 protocol. The data reveals a prevalence of articles published in journals (74%) as opposed to conference proceedings (21%). The majority of journal papers were primarily published in 2017 and 2020, while proceedings predominantly featured publications from 2019. In addition, a small fraction (5%) of the included studies consisted of book chapters that were published in 2012 and 2013.

Figure 3: Research Methods used Across Reviewed Studies



The articles reviewed employed a wide variety of methods. Figure 3 presents a count of the methods used across the 42 articles. It is important to note that two articles used multiple methods, so a total of 44 methods are reported in Figure 3. Our analysis uncovered that around 80% of the studies were empirical, indicating that the results were derived from actual experiments. The majority (n = 27) of the articles used quantitative methods, while only three articles used qualitative methods. Nineteen of the quantitative articles employed experimental or quasi-experimental designs where an embodied instructional intervention was assessed against a comparison group. Of these 19 articles, 73.6% (n = 14) of the articles reported larger learning gains for students engaged in embodied learning activities, while the remaining five found no difference between the embodied and the non-embodied (or less embodied) conditions. Importantly, none of the articles reported larger learning gains for the non-embodied conditions. While we did not categorize the comparison conditions, future research should examine both the effect sizes and the comparison conditions before strong conclusions should be drawn about the magnitude of the learning gains one can reasonably expect from embodied interventions in STEM courses.

As our study aimed to evaluate recent advancements in research on visuospatial skills in STEM disciplines, we infer the following themes from our analysis.

A. Demographic Characteristics

As illustrated in Figure 4, this general theme emerged from three distinct code categories we observed in the experimental study reports. The majority of researchers (63%) have conducted visuospatial studies on children in various educational contexts, ranging from early childhood to high school, which consisted of three studies ([13]–[15]) focused on students who sit in pre-K and kindergarten, sixteen studies ([16], [17], [26]–[31], [18]–[25]) targeting the elementary and middle schoolers, and one study [32] examined high-school student population. The remaining documents (37%) investigated visuospatial skills in the context of higher education, including eleven articles ([33], [34], [43], [35]–[42]) concerned with students, while another single study [44] involved university instructors.

Figure 3: Categories of Demographic Characteristics

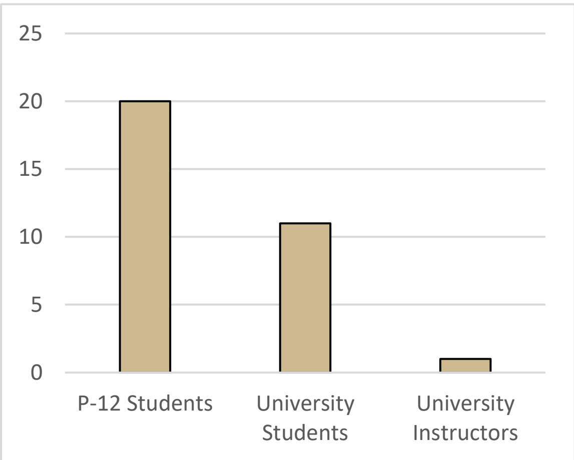
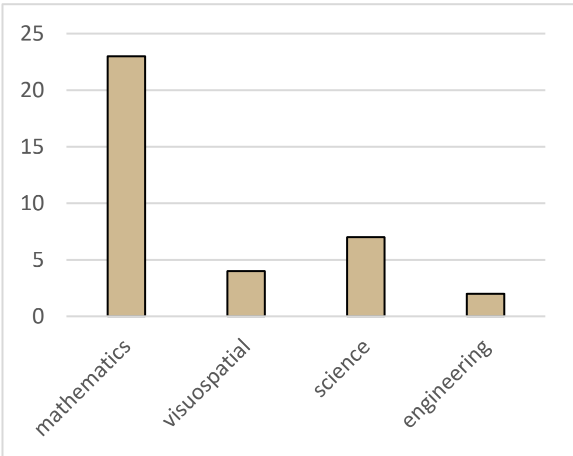


Figure 4: Classification of Application Domains



B. Application Domains

Figure 5 shows four general domains that leveraged the principles of embodied cognition in their practices, spreading in 86% of the studies reviewed. Notably, mathematics emerged as the top field that applied embodied cognition, appearing in 23 articles ([13], [15], [28]–[30], [32], [39]–[41], [44]–[46], [17], [47]–[49], [20]–[25], [27]). Followed by science at the second place ([14], [26], [31], [35], [37], [42], [43]), with visuospatial training ([16], [18], [19], [38]), and engineering [33], [34] occupying the subsequent positions.

C. Visuospatial Test Instruments

A cumulative of 38 instruments were discussed in detail throughout the papers. We categorized them into four distinct themes, as depicted in Figure 6. Mental test instruments dominated the chart as reported by 34% articles ([13], [16], [34], [35], [37], [17], [19]–[21], [23], [25], [26], [33]). Psychometric tools such as the Mental rotation test (MRT), Purdue Spatial Visualizations Test: Rotations (PSVT:R), Mental Cutting Test (MCT), and Bruininks-Oseretsky Test of Motor Proficiency (BOT II) were among the standardized mental tasks employed. The next instruments, game-based play (29%) and body movements (24%), ranked in successive positions. We grouped physical and computerized play activities involved in [15], [18], [43], [19], [20], [24], [28], [30], [32], [35], [41] into the former category. On the other hand, learning activities that incorporate the physical motion of body parts ([14], [17], [21], [22], [29], [31], [40], [42], [44]) were classified into the latter category. Ultimately, our analysis discovered that a mere 13% of studies ([19], [21], [27], [38], [39]) discussed the utilization of blocks as their visual and spatial instrument.

Figure 5: Visuospatial Instruments Theme

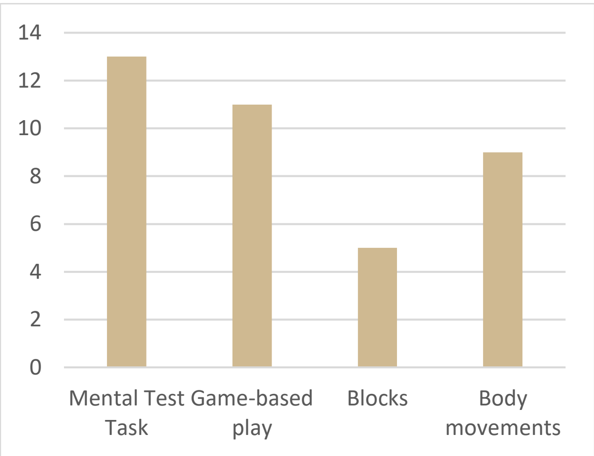
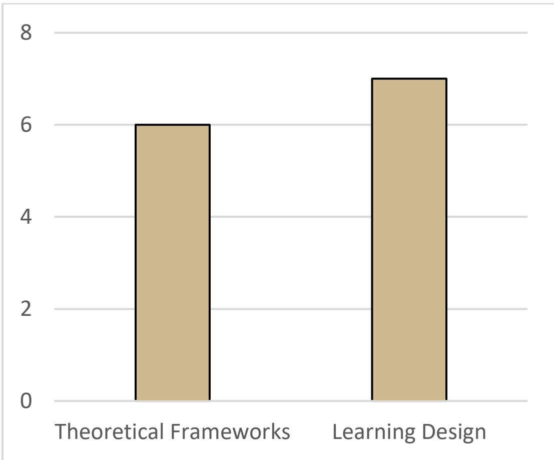


Figure 6: Theory and Design Theme



D. Theory and Design

Our empirical and literature studies analysis identified two prevalent themes concerning theoretical frameworks and design principles in STEM learning environments (Figure 7). Within the category of theoretical frameworks (46% of studies; [32], [45], [46], [50]–[52]), the primary focus centered on the role of theory in understanding embodied cognition and its implications for STEM teaching and learning. Conversely, 54% of the papers ([23], [36], [47]–[49], [53], [54]) deliberated on delineating the methodologies employed in crafting educational tools for STEM learning.

IV. Discussion

The results of the present study highlight that the majority of visuospatial research involving embodied cognition in STEM education was conducted at the elementary and middle school level, with the greatest focus on mathematics learning. These findings revealed that visuospatial and motor skills contribute to success in mathematics. Using the Bruininks-Oseretsky Test of Motor Proficiency (BOT-2) Complete Form, which is a valid and reliable standardized motor assessment tool, Macdonald et al. [25] and Dejonckcheere et al. [20] proved that first graders' motor skills were highly correlated with their abilities in math, regardless whether they learn mathematics using paper and pencil or computerized games. Interestingly, visuomotor skills that involve balance coordination of body movement and visual stimuli while moving either in active mode (e.g., walking, running) or passive mode condition (i.e., sitting) also influence the ability to do arithmetic calculations, particularly in numbers addition and subtraction. Pieces of evidence from studies conducted by Flanagan [22], Lugli et al. [39], and Marghetis et al. [40] had shown that both elementary and university students produced more correct calculations when sitting while their fingers, hands, or eyes moved, or when sitting on a wheelchair while making circular movement. Further studies even showed that when learners moved in active modes [11], engaged in full-body movement [15], or turned their body toward right and left direction [29] were able to effectively solve addition and subtraction of two and three-digit numbers problems, as well as improve their understanding of computer programming concepts. All of these studies provided convincing evidence as to Weisberg and Newcombe [8], who suggested incorporating embodied cognitive tools and gestures in transforming STEM education.

Our study discovered various theories employed by researchers in designing a mathematics learning environment that equips students with embodied cognitive tools to support gestural movements. Abrahamson et al. [45] introduced the framework of embodied design as a way to incorporate the embodiment approach into mathematics learning activities. This concept applies to design tools that aim to foster the development of sensorimotor schemes, which serve as the foundation for understanding and applying mathematical concepts. The two most important aspects of this theoretical framework, to which designers of embodied cognitive tools must focus their attention, are perception-based embodied design and action-based embodied design. The former aspect focuses on ideas related to likelihood, slope, density, and proportional equivalence in geometrical similarity. In this design, students are encouraged to express their initial perspective on a situation before engaging in modeling, reflecting, and discussing their views. These approaches aim to improve their understanding of a given situation. As for the second aspect, action-based embodied design aims to establish a foundation for mathematical concepts by utilizing students' natural abilities, with a specific focus on their adaptable sensorimotor skills. In this design, students utilize technology interventions to manipulate objects to reach a specific goal state. We identified three studies included in this systematic review ([18], [20], [41]) that implemented both aspects of embodied design frameworks.

These three studies incorporate game-based play using mouse control. However, only two of them focused on mathematics learning, and only one of them was intended to be used by elementary schoolers. In a game-based play developed by Dejonckheere et al. [23], children engaged in a numerical game against computer, where they had to throw a dice, stop it, and move the pawn along 11 blue blocks containing a number ranging from 1 to 10. The action-based embodied design occurred when the children clicked a mouse control and dragged the pawn until they reached the end of the line. As for the perception-based embodied design, the game designers provided a mouse test game, which aimed to familiarize the children with the skill of manipulating a computer mouse. The experiment using this game-based play gives evidence that there is a considerable correlation between motor skills and math learning.

Another theoretical framework we found related to designing embodied cognitive tools for learning math was proposed by Nathan and Walkington [32]. Their theory is called grounded and embodied mathematical cognition (GEMC), which utilizes action-cognition transduction (ACT) to explore how body movement facilitates mathematical reasoning. GEMC suggests that the actions of participants can act as inputs that can guide the cognition-action system toward related cognitive states. Unlike the framework of embodied design, which focuses on movement only, GEMC emphasizes language to direct movements. Nathan and Walkington designed a game called The Hidden Village as an embodied cognitive tool for geometry learning. In this game, students were given a set of written instructions on the screen that asked them to respond by moving their hands with the circular cycle while also explaining verbally. Unfortunately, we could not find any studies selected in this systematic review that applied GEMC for math learning.

V. Conclusion

This systematic review provides an overview of the latest scientific progress in visual and spatial abilities within STEM education. Our findings indicate that mathematics learning is the most dominant field that embraces embodied cognition; this implies that visuomotor skills play a significant role in achieving success in mathematics. We have also identified two theoretical frameworks: embodied design and grounded and embodied mathematical cognition (GEMC); these serve as the foundation for the design and development of embodied cognitive tools. While Embodied design and GEMC were used to design mathematics learning tools, we believe that researchers can apply a modification of the frameworks to other STEM disciplines, including physics, chemistry, biology, and engineering courses. We recognized that there is a lack of research on visuospatial and embodied cognition involving participants from higher education; we strongly recommend additional studies for observing such participants, mainly recruiting college instructors. We also promote the utilization of blocks in future studies on this topic. Furthermore, as this study relied on only two databases for data collection, it is anticipated that future research can incorporate more databases to provide a broader perspective.

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Appendix A

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
1	D. Abrahamson, M.J. Nathan, C. Williams-Pierce, C. Walkington, E.R. Ottmar, H. Soto, & M. W. Alibali (2020). The Future of Embodied Design for Mathematics Teaching and Learning	Theoretical	10.3389/feduc.2020.00147	Journal Article	The article provides an expansive summary of theories of embodied cognition, and a summary of design principles for mathematics instruction that uses body movement, gesture, and/or physical and digital manipulatives. Each design principle is supported with findings from recent research and exemplar embodied pedagogical designs for math instruction.
2	D.R. Becker, A. Miao, R. Duncan, & M.M. McClelland (2014). Behavioral self- regulation and executive function both predict visuomotor skills and early academic achievement	Correlational Cross-Sectional	10.1016/j.ecresq.2014.04.014	Journal Article	This article presents the results of a cross-sectional correlational study that examined the relationship between executive functioning, visuo-spatial skills and math performance of pre-kindergarten and kindergarten students. The results indicate that visuo-spatial skills are related to executive functioning. Further math performance is related to both executive functioning and visuo-spatial skills.
3	M. Blüchel, J. Lehmann, J. Kellner, & P. Jansen (2013). The improvement in mental rotation performance in primary school-aged children after a two-week motor-training	Empirical / Correlational Cross-Sectional (Pre/Post Design)	10.1080/01443410.2012.707612	Journal Article	This article presents the results of a cross-sectional empirical study where half of the students received motor skills training (unrelated to the outcome measures). This study examined visuo-spatial skills, and academic performance of 3rd grade students with and without the training. The results indicate that there is a correlation between mental rotation ability and math grades, but not grades in science,

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
					language arts, or music. In addition, there is weak evidence (.05 < p < .10) that students who received the motor training improved more on a mental rotation task.
4	H. Burte, A. L. Gardony, A. Hutton, & H. A. Taylor (2017). Think3d!: Improving mathematics learning through embodied spatial training	Correlational Cross-Sectional (Pre/Post Design)	10.1186/s41235-017-0052-9	Journal Article	This article presents the results of a cross-sectional correlational study that examined the relationship between visuo-spatial skills and math ability of 3rd – 6th grade students following the completion of an embodied spatial training program (Think3d!). Pre and post assessment were completed 2 weeks apart with the embodied spatial training program in between. The results indicate a marginal increase in math scores, though older students appear to improve more than younger students. Mental rotation skills improved for 3rd graders but not for older students.
5	J. S. Chang (2017. Tangible and virtual interactions for supporting spatial cognition	Research Summary	10.1145/3064857.3079163	Conference Proceedings	This article provides a short summary of the research being conducted by the lab. The research focuses on using virtual reality to teach spatial cognition.
6	P-T. Chiu, H. Wauck, Z. Xiao, Y. Yao, & W-T. Fu2 (2018). Supporting spatial skill learning with gesture- based embodied design	Experimental Between Subjects Design	10.1145/3172944.3172994	Conference Proceedings	This article presents the results of an experimental study where fifteen 8–12-year-olds built objects in a digital game under two conditions: using a mouse, and using gestures captured by the LEAP motion sensor. The results indicated that the participants were more efficient when using gestures.

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
7	G. Città, M. Gentile, M. Allegra, M. Arrigo, D. Conti, S. Ottaviano, F. Reale, & M. Sciortino (2019). The effects of mental rotation on computational thinking	Quasi Experimental & Correlational	10.1016/j.compedu.2019.103613	Journal Article	This article presents the results of a correlational study where ninety-two 6–10-year-olds completed an activity where they enacted the movement of robots following computer programming instructions. The study measured spatial reasoning, using a mental rotation test, and computational thinking using a paper and pencil activity where students wrote an algorithm to solve a problem. The result showed a relationship between mental rotation and computational thinking.
8	T. Dackermann, U. Fischer, H-C. Nuerk, U. Cress, & K. Moeller (2017). Applying embodied cognition: from useful interventions and their theoretical underpinnings to practical applications	Theoretical	10.1007/s11858-017-0850-z	Journal Article	This article presents a review of studies of elementary students that examine the learning of numeracy and enactment of concepts in physical space. Following this, the authors present a theoretical framework for embodied training effects.
9	E. Davishahl, T. Haskell, L. Singleton, & M. P. Fuentes (2021). Do They Need To See It To Learn It? Spatial Abilities, Representational Competence, and Conceptual Knowledge in Statics	Quasi-Experimental, Pre-Post Design & Correlational	Unassigned	Conference Proceedings	This article presents a quasi-experimental study examining changes in pre/post scores of community college students who would manipulate physical manipulatives while learning in statics. Gains in spatial reasoning skills were found. A relation between spatial reasoning and content learning of vectors and statics concepts was found.
10	E. Davishahl, L. Singleton, & T. Haskell (2020). Engaging	Proposal Summary	Unassigned	Conference Proceedings	This article presents a summary of proposed studies that would be conducted in the future where

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
	STEM learners with hands-on models to build representational competence				university engineering students would manipulate physical manipulatives while learning in statics. A hypothesized relationship between spatial cognition skills and learning was predicted by the authors.
11	P. J. N. Dejonckheere, A. Desoete, N. Fonck, D. Roderiguez, L. Six, T. Vermeersch, & L. Vermeulen. (2014). Action-based digital tools: Mathematics learning in 6-year-old children	Experimental Between Subjects Design	10.14204/ejrep.32.13108	Journal Article	This article presents experimental investigation that examines the impact of an intervention where first grade students manipulate a computer mouse to complete a computer activity to learn about the number line. Compared to the control group, who did nothing, students completing the game had better performance on the number line tasks. In addition, those with lower motor skills demonstrated larger performance gains.
12	D. DeSutter, & M. Stieff (2020). Designing for spatial thinking in STEM: Embodying perspective shifts does not lead to improvements in the imagined operations	Experimental Between Subjects Design	Unassigned	Conference Proceedings	This article presents an experimental investigation that examines the effect of a computer simulation that rotates a virtual image of molecular structures based on the users' head position, simulating how one might view a physical model. The comparison condition used a mouse to click through the instructional slide show. The results showed no learning gains for either condition and no difference between conditions.

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
13	D. DeSutter, & M. Stieff (2017). Teaching students to think spatially through embodied actions: Design principles for learning environments in science, technology, engineering, and mathematics	Theoretical	10.1186/s41235-016-0039-y	Journal Article	The article presents a review of embodied cognition, focusing on evidence supporting theories of embodied cognition. The article then presents a collection of design principles for designing and testing learning environments designed to teach using embodied cognition.
14	D. Di Iorio, A. Santaniello, & F. G. Paloma (2015). Body in Education: Terzi Method	Review	10.1016/j.sbspro.2015.01.1020	Journal Article	This article presents a very brief review of the Terzi method for embodied exercises.
15	C. Duijzer, M. Van den Heuvel-Panhuizen, M. Veldhuis, M. Doorman, & P. Leseman (2019). Embodied Learning Environments for Graphing Motion: a Systematic Literature Review	Review	10.1007/s10648-019-09471-7	Journal Article	This article presents a systematic review of embodied learning environments designed to teach graphing. The results suggest that interventions that connect student movements to graphing are beneficial for learning about mathematical graphing.
16	L. M. Flanagan-Mendez, M. J. Contreras, I. C. Mammarella, T. Feraco, & C. Managhetti (2020). Mathematical achievement: The role of spatial and motor skills in 6–8-year-old children	Correlational	10.7717/peerj.10095	Journal Article	This article presents the results of a correlational study of 305 students between the ages of 6 and 8, who completed spatial visualization and mathematics achievement tests. The results show a relationship between spatial reasoning skills and mathematics scores even after controlling for age.

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
17	R. Flanagan (2013). Effects of learning from interaction with physical or mediated devices Spatial Learning and Reasoning Processes	Experimental Between Subjects Design	10.1007/s10339-013-0564-2	Journal Article	This article presents an experimental investigation that examines the difference between third grade students learning math skills using either a physical or virtual abacus. The results showed that students using the physical abacus did better on performance and transfer tasks.
18	A. U. Gold, P. M. Pendergast, C. J. Ormand, D. A. Budd, J. A. Stempien, K. J. Mueller, & K. A. Kravitz (2018). Spatial skills in undergraduate students- Influence of gender, motivation, academic training, and childhood play	Correlational	10.1130/GES01494.1	Journal Article	This article presents the results of a correlational study of 345 undergraduate geology students, who completed spatial visualization and demographics questionnaires. The results show a relationship between spatial reasoning skills and standardized test scores, gender and college major differences in spatial reasoning skills, and a relationship between experience with construction-based toys as children and spatial reasoning skills.
19	D. D. Hutto, M. D. Kirchhoff, & D. Abrahamson (2015). The enactive roots of STEM: Rethinking educational design in mathematics	Theoretical	10.1007/s10648-015-9326-2	Journal Article	This article presents a theoretical review of the radical enactive, embodied view of cognition. Following a thorough review, this article argues that the radical enactive, embodied view of cognition can be usefully extended into the domain of science, technology, engineering, and mathematics (STEM) learning.

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
20	P. J. Kellman, & C. M. Massey (2013). Perceptual Learning, Cognition, and Expertise	Theoretical	10.1016/B97 8-0-12- 407237- 4.00004-9	Book Chapter	This article presents a theoretical review of perceptual learning in complex cognitive tasks. The review presents evidence from experimental and neuroscientific research to support the foundational importance of perceptual and spatial reasoning in learning complex STEM content and skills.
21	S. Kornkasem, & J. Black (2015). CAAD, cognition & spatial thinking training	Experimental Between Subjects Design	Unassigned	Conference Proceedings	This article presents two experimental investigations involving graduate students with limited STEM experience that examined ?? learning in physical and virtual learning environments. The results indicated that virtual manipulatives improved spatial reasoning skills more than physical manipulatives.
22	R. Samuelsson (2019). Embodied reasoning with digital tools in the preschool ecology: science learning beyond digital/analogue dichotomies	Ethnography	10.1145/3343031.3351017	Conference Proceedings	This article presents the results of an ethnography of preschool students who are engaged in science learning with technology. The results detail how students use their embodied experiences during play to think and reason about science concepts. The results support the idea that cognition is both situated and embodied.

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
23	T. Link, K. Moeller, S. Huber, U. Fischer, & H-C. Nuerk (2013). Walk the number line - An embodied training of numerical concepts	Experimental Between Subjects Design	10.1016/j.tine.2013.06.005	Journal Article	This article presents an experimental investigation that examined the effect of an embodied intervention for elementary students learning about the number line. In the original article, the results indicated that students learned better and had greater transfer with the embodied intervention. A subsequent corrigendum presented a reanalysis which indicated that there were no learning differences between the intervention and the control. However, the embodied intervention still resulted in greater transfer to new tasks.
24	L. Lugli, S. D'Ascenzo, A. M. Borghi, & R. Nicoletti (2018). Clock walking and gender: How circular movements influence arithmetic calculations	Experimental Within persons 2x2 design	10.3389/fpsyg.2018.01599	Journal Article	This article presents a within-persons experimental investigation that examined the effect of movement and direction on numeric calculations of undergraduate students. Across eight trials, students were tasked with either continually adding or subtracting a constant value from a three-digit value. The results indicate that participants were move successful when adding, when actively moving (walking), and when moving in a clockwise circle regardless of whether the participant was actively walking or passively being pushed on a wheelchair.
25	K. Macdonald, N. Milne, R. Orr, & R. Pope (2020). Associations between motor	Correlational	10.1186/s12887-020-1967-8	Journal Article	This article presents the results of a correlational study of 55 Year 1 students (mean age of 6.8 years) examining the relationship between motor

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
	proficiency and academic performance in mathematics and reading in year 1 school children: A cross- sectional study				proficiency and math ability. The results indicate a relationship between fine and gross motor proficiency and mathematics ability.
26	T. Marghetis, D. Landy, & R. Goldstone (2016). Mastering algebra retrains the visual system to perceive hierarchical structure in equations	Correlational	10.1186/s41235-016-0020-9	Journal Article	This article presents the results of a correlational study of 150 adults online who completed an algebra task and an object-based attention task. The results indicate that there is a relationship between algebraic order of operations knowledge and object-based attention.
27	T. Marghetis, R. Nunez, & B. K. Bergen (2014). Doing arithmetic by hand: Hand movements during exact arithmetic reveal systematic, dynamic spatial processing	Experimental Within Subjects design	10.1080/17470218.2014.897359	Journal Article	This article presents the results of a correlational study of 44 undergraduate students who engaged in solving simple arithmetic problems (addition and subtraction) and selected the correct answers from two options located in the upper left and upper right corners of a computer screen. The results indicate that participants are biased in the mouse movement in the direction of the operations movement on the number line. That is that participants tended to initially move to the left for subtraction problems and to the right for addition problems even when the correct answers are located in the opposite direction.

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
28	L. E. Margulieux (2019). Spatial encoding strategy theory the relationship between spatial skill and STEM achievement	Review	10.1145/3291279.3339414	Conference Proceedings	This article presents a review of students within STEM education that examines the relationship between STEM learning and spatial reasoning. Following the review, the article proposes the spatial encoding strategy theory to explain the cognitive mechanisms connecting spatial skill and STEM achievement and presents a testing and validation plan for examining the proposed theory.
29	G. McCollum (2022). Sensorimotor Underpinnings of Mathematical Imagination: Qualitative Analysis	Qualitative Case Study	10.3389/fpsyg.2021.692602	Journal Article	This article presents a case study of eleven university mathematics instructors who were asked to describe their mental imagery associated with algebraic concepts. The results indicated that the objects representing algebraic concepts were typically situated with respect to the instructors' bodies. In addition, the imagery of the abstract mathematical concepts and the physical body of the instructors behaved as a dyad (movements of each were coordinated) when describing the abstract mathematical concepts.
30	R. Menary, & M./ Kirchoff (2014). Cognitive Transformations and Extended Expertise	Theoretical	10.1080/00131857.2013.779209	Journal Article	This article presents a theoretical review of the process of the development of expertise in mathematics and describes the importance of sensory-motor skills in mathematics expertise.

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
31	K. Mix, & Y-L. Cheng (2012). The Relation Between Space and Math. Developmental and Educational Implications	Review	10.1016/B97 8-0-12-394388-0.00006-X	Book Chapter	This article presents a review of the relationship between spatial and mathematics abilities.
32	M. Nathan, & C. Walkington (2017). Grounded and embodied mathematical cognition: Promoting mathematical insight and proof using action and language	Theoretical	10.1186/s41235-016-0040-5	Journal Article	This article presents a theory of grounded and embodied mathematical cognition. The article draws on the results of several research studies that investigate the relationship between action-cognition transduction and mathematical reasoning.
33	R. Lindgren, & D. DeLiema (2022). Viewpoint, embodiment, and roles in STEM learning technologies	Theoretical	10.1007/s11423-022-10101-3	Journal Article	This article presents a framework for the design of immersive and interactive STEM learning technologies. The framework integrates three components; visual viewpoint, embodied interaction, and the role of the learner.
34	J. Plummer, P. Udomprasert, A. Vaishampayan, S. Sunbury, K. Cho, H. Houghton, E. Johnson, E. Wright, P. M. Sadler, & A. Goodman (2022). Learning to think spatially through curricula that embed spatial training	Experimental Between Subjects Design	10.1002/tea.21754	Journal Article	This article presents a mixed methods experimental study of middle school students who engaged in a unit that involved embodied astronomy lessons or were engaged in instruction as usual (the comparison condition is not described in the article). The results indicate that the embodied lessons lead to larger learning gains for all students except for those with the highest pre-test scores.

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
35	M. Ruiter, S. Loyens, & F. Paas (2015). Watch your step children! learning two- digit numbers through mirror-based observation of self- initiated body movements	Experimental Between Subjects Design	10.1007/s10648-015-9324-4	Journal Article	This article presents an experimental study of 118 first-grade students where students were taught two-digit numeracy through movement or non-movement-based lessons. The results indicate that students in the movement groups outperformed students in the non-movement groups.
36	E. M. Schoevers, P. P. Leseman, & E. H. Kroesbergen (2020). Enriching Mathematics Education with Visual Arts: Effects on Elementary School Students' Ability in Geometry and Visual Arts	Quasi-Experimental	10.1007/s10763-019-10018-z	Journal Article	This article presents a quasi-experimental study that evaluates Mathematics, Arts, and Creativity in Education (MACE) program on elementary students' math learning. Within the MACE program student construct 3D representations of 2D paintings and use physical manipulatives to explore the mathematical ideas. The study engaged 2,909 students across 121 classes and 57 schools. Compared to the traditional curriculum, students in instructed through the MACE program there was no difference in mathematics learning.
37	E. Sixtus, N. Linder, K. Lohse, & J. Lonnemann (2023). Investigating the influence of body movements on children's mental arithmetic performance	Experimental Within Subjects Design	10.1016/j.actpsy.2023.104003	Journal Article	This article presents a within subjects' experimental study of 48 3rd and 4th grade students that examined the effect of movement and direction on numeric calculations of undergraduate students. Across eight trials, students were tasked with either continually adding or subtracting a constant value from a three-digit value while either moving or standing. The results indicate that participants were more successful when the direction in which they were facing

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
					aligned with the operations direction on the number line. There was no effect for whether students were moving or not.
38	M. Stieff, M. E. Lira, & S. A. Scopelitis (2016). Gesture Supports Spatial Thinking in STEM	Experimental Between Subjects Design	10.1080/07370008.2016.1145122	Journal Article	This article presents two experimental studies. In the first study, 77 undergraduate organic chemistry students were either instructed using text, observing instructor gestures, or producing gestures conditions. Students who were engaged in producing gestures performed better than students in the other two conditions. In the second study, 104 undergraduate organic chemistry students were instructed by either producing gestures or not, and either building models using manipulatives using a 2x2 design. The results indicated the presence of an interaction effect where physical models improved performance in the no-gesture condition, but not in the gesture condition.
39	W. Sung, J. Ahn, & J. Black (2017). Introducing Computational Thinking to Young Learners: Practicing Computational Perspectives Through Embodiment in Mathematics Education	Experimental Between Subjects Design	10.1007/s10758-017-9328-x	Journal Article	This article presents an experimental study where kindergarten and first grade students completed computational perspective practice or not and were either engaged in high or low embodied instruction (2 x 2 Design). The results indicate that the level of embodiment was related to mathematics and computational thinking learning.

No.	Author(s), Year & Title	Article Method(s)	DOI	Reference Type	Description
40	W. Sung, & J. Black (2020). Factors to consider when designing effective learning: Infusing computational thinking in mathematics to support thinking-doing	Quasi-Experimental	10.1080/15391523.2020.1784066	Journal Article	This article presents a quasi-experimental study where 134 second to fourth grade students completed computational perspective practice or not, and were either engaged in high or low embodied instruction (2 x 2 Design). Participants were not randomly assigned, rather groups of students were randomly assigned to each condition. The results indicate that the level of embodiment was related to mathematics and computational thinking learning.
41	A. Vaishampayan, J. Plummer, P. Udonprasert, & S. Sunbury (2019). Use of spatial sensemaking practices in spatial learning	Cross-Sectional Observation Study	Unassigned	Conference Proceedings	This article presents an observational study of 185 eleven- and twelve-year-olds engaged in a 10-day season curricular unit. The qualitative conclusions indicate that students used body-based and manipulative cognitive strategies to understand and explain the science content.
42	S.P.W. Wu, J. Corr, & M. A. Rau (2019). How instructors frame students' interactions with educational technologies can enhance or reduce learning with multiple representations	Quasi-Experimental Between Subjects Design	10.1016/j.compedu.2018.09.012	Journal Article	This article presents a quasi-experimental study where 693 undergraduate chemistry grade students engaged in either drawing molecular models, building physical molecular models, or the "business as usual" condition without framing prompts. The results indicated no difference in spatial skill gains between the conditions, but the physical molecular modeling condition exhibited larger gains on the transfer task.