Received: 27 July 2022 | Accepted: 21 April 2023

DOI: 10.1002/rev3.3400

STATE OF THE ART REVIEW

Review of Education BERA

# Educational interventions involving physical manipulatives for improving children's learning and development: A scoping review

**Elizabeth M. Byrne**[1,2] | **Hanne Jensen**[3] | **Bo Stjerne Thomsen**[3] | **Paul G. Ramchandani**[1]

[1]Faculty of Education, PEDAL Research Centre, University of Cambridge, Cambridge, UK

[2]School of Psychology, University of East Anglia, Norwich, UK

[3]LEGO Foundation, Billund, Denmark

**Correspondence**
Elizabeth M. Byrne, School of Psychology, University of East Anglia, Norwich, UK.
Email: elizabeth.byrne@uea.ac.uk

**Funding information**
LEGO Foundation

**Abstract**

Physical manipulatives (PMs) are concrete objects used during hands-on learning activities (e.g., building blocks, fraction tiles, counters), and are widely used in primary-school teaching, especially during maths instruction. This scoping review collated studies that have examined the effectiveness of educational PM interventions with pre-primary and primary-age children. A total of 102 studies met the inclusion criteria and were synthesised in the review. Most studies included a sample of children aged 4–6 years and were conducted in a school setting. They spanned 26 different countries, but almost all took place in high- or middle-income contexts, mainly in the USA. Interventions were grouped into three main learning domains: maths, literacy and science. Considerable heterogeneity was identified across the review studies in terms of the PMs and hands-on activities used (e.g., block building, shape sorting, paper folding, enactment with figurines). Evidence relating to effectiveness of the intervention programmes was synthesised, with the most promising findings identified in the maths domain. Benefits to children's spatial, literacy and science skills were also reported. Overall, however, the evidence was mixed: other studies found that PMs were not associated with learning benefits, and many were hindered by methodological shortcomings. This calls for caution when drawing conclusions about the overall

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2023 The Authors. *Review of Education* published by John Wiley & Sons Ltd on behalf of British Educational Research Association.

effectiveness of PM interventions. Nevertheless, the findings illustrate the many ways hands-on PM activities can be incorporated into children's early learning experiences. Recommendations for further research and for using PMs in practice are made.

**KEYWORDS**

early learning, interventions, physical manipulatives, scoping review

### Context and implications

#### Rationale for this study

Physical manipulatives (PMs) are used during hands-on learning activities and promote children's active involvement in learning. The review sought to map a broad range of interventions using PMs.

#### Why the new findings matter

Findings reveal gaps in the research and highlight the many facets to consider when developing and testing educational interventions using PMs.

#### Implications for practitioners

Recommendations for using PMs in practice: (a) choose materials and activities that are age-appropriate and focused on the learning goal; (b) consider the type and amount of instructional guidance needed (adjusted based on learning content and children's needs); and (c) consider the level of physical interaction afforded by PMs and activities and its importance for the learning goal.

# INTRODUCTION

## Background

Physical manipulatives (PMs) are concrete materials used during hands-on learning activities, typically to help primary-age children learn maths (Carbonneau et al., 2013). PMs can include objects such as building blocks, fraction tiles, counters, figurines, toys and props. Educational interventions involving PMs have largely been centred on enhancing children's maths abilities (as seen in reviews by Carbonneau et al., 2013; Lafay et al., 2019; Sarama & Clements, 2009), but there is emerging research in other learning domains such as reading, spatial cognition and science (Skene et al., 2022; Toub et al., 2018; van Schijndel et al., 2010; Vander Heyden et al., 2017). Research on the effectiveness of PM interventions is atomised, with significant variation among intervention studies in the types of PMs and activities used, the level of adult support provided, and the learning domains targeted. The purpose of this scoping review is to provide a comprehensive overview of the current research on PM interventions.

Evidence suggests that object play is beneficial for children's learning and development (for overviews, see Pellegrini & Gustafson, 2005; Whitebread, 2012, 2019). Infants are naturally curious, and as soon as they can grasp and hold items, they engage in early exploratory and manipulative behaviours such as mouthing, hitting, dropping and stroking (sensorimotor play). By age two, children begin to arrange and sort objects, and by age four, they start to engage in building and construction behaviours (Whitebread, 2012). Interacting with physical objects allows children to explore and discover concepts such as shape, size, weight and space, helping to establish a solid foundation for spatial and maths thinking (Botha et al., 2005; Charlesworth & Lind, 2003; Pound, 2006).

As well as helping young children develop fundamental fine and gross motor skills, early manipulative behaviours are closely related to the development of spatial reasoning (Caldera et al., 1999; Jirout & Newcombe, 2015; Levine et al., 2012; Möhring & Frick, 2013), a key cognitive ability that is important for everyday tasks such as remembering the location of objects and events. When children engage in activities such as block play, they are tapping into and honing their spatial skills, imagining how blocks can fit together and be arranged, manipulating the materials both mentally and physically.

Studies also indicate that early play with PMs such as blocks is associated with children's concurrent and later maths performance in school (Bower et al., 2020; Wolfgang et al., 2001, 2003). Early spatial skills are predictive of children's maths performance (Casey et al., 2012; Clements & Sarama, 2008; Fernández-Méndez et al., 2020; Gunderson et al., 2012; Mix & Cheng, 2012; T. Thompson, 2016; Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2014; Verdine, Golinkoff, Hirsh-Pasek, Newcombe, Filipowicz et al., 2014) and are thought to underpin learning of maths concepts such as geometry, mental arithmetic, magnitude estimation, counting and algebra (Battista, 1990; Kyttälä et al., 2003; Kyttälä & Lehto, 2008; Thompson et al., 2013; Tolar et al., 2009). They also predict the likelihood of children later pursuing and succeeding in STEM-based subjects and careers (Khine, 2016; Wai et al., 2009).

Studies also provide evidence for the learning benefits of PMs in other domains such as literacy and science. Playing with PMs can aid children's language development, as the materials act as concrete, tangible representations of the words they are learning (for example, playing with toy animal figurines to learn their names) (Glenberg, 2008). Hands-on activities also foster children's scientific reasoning, providing them with opportunities to experiment, test hypotheses and understand concepts such as cause-and-effect (Morris et al., 2012; Zimmerman, 2007), and some arguing that physical interaction with the environment is crucial for scientific learning (Zacharia et al., 2012). This review will explore the different learning domains in which PMs have been used.

Theoretical perspectives for how PMs may support early learning are embedded in a developmental framework of cognitive constructivism and embodied cognition (for an overview, see Marley & Carbonneau, 2014). These theories posit that young children's physical interaction with the environment is crucial for their learning and development (Bruner, 1964; Montessori, 1964; Piaget, 1962; Piaget & Inhelder, 2014). For example, Bruner (1964) proposed that children rely on different representational forms throughout different stages of cognitive development, starting with physical exploration of the environment (enactive), then images (iconic), and words (symbolic). Similarly, the *concrete-to-abstract* approach, based on Piaget's (1952) cognitive theory that concrete-operational (literal) thinking is a prerequisite for formal-operational (abstract) thinking, suggests that PMs help children strengthen their concrete thinking before moving on to more complex, abstract ideas (Taylor & Boyer, 2020), and connect learned concepts to real-world experiences (Holmes, 2013; Rittle-Johnson & Koedinger, 2005). Theories of embodied cognition and evidence from self-performed tasks also support the idea that physical actions with PMs help children learn new concepts (Barsalou, 2007; Engelkamp et al., 1994; Marley & Carbonneau, 2014; Mulligan & Hornstein, 2003; Wilson, 2002).

Although research and theories indicate that PMs can enhance children's learning, it is important to also consider the need for appropriate instructional guidance and scaffolding to ensure that children use PMs in a way that appropriately represents the concept being learned (Carbonneau et al., 2013). Therefore, this review will also explore the different types of instructional guidance used in PM interventions.

There is ongoing debate about the relative effectiveness of child-led or adult-led learning (Fisher et al., 2012; Hirsh-Pasek et al., 2010; Pyle et al., 2017; Pyle & Danniels, 2017; Skene et al., 2022; Weisberg et al., 2016; Yu et al., 2018; Zosh et al., 2017, 2018). Zosh et al. (2018) have suggested that it might be more helpful to consider these approaches to learning as a spectrum. Along this spectrum there are different levels of child autonomy and adult guidance. At one end is *free play*, where children initiate and lead activities, without an extrinsic goal. At the other end is *direct instruction*, an adult-led approach with a clear learning objective. In the middle, are *guided play*, with sharing of control between children and adults, and *games*. Guided play encourages children's active participation and engagement in learning (Zosh et al., 2018). It is characterised by: (a) child agency, meaning children have control over their actions and play; (b) adult guidance, which includes initiating a playful activity/environment and using scaffolding techniques such as prompts, co-play, open-ended questions, modelling behaviours/actions, setting challenges, and adjusting to children's needs/interests; and (c) a learning goal such as acquiring target vocabulary or shape knowledge (Skene et al., 2022; Weisberg et al., 2013; Weisberg & Hirsh-Pasek, 2013). Although educational games are directed by children, they are designed by adults, have a clear objective and follow set rules, affording children less autonomy.

By defining learning and play along a continuum, it can be difficult to distinguish between different pedagogical approaches. For instance, the degree of child choice and adult involvement varies among guided play interventions, making it hard to determine where guided play ends and free play or direct instruction begin. Additionally, there is no ‘one size fits all’ approach to children's education, and educators often use a combination of approaches, adapting to children's needs for guidance from one moment (or task) to the next, as they gain proficiency.

Evidence from multiple review studies and meta-analyses indicate that maths interventions using PMs improve children's maths achievement more than interventions without PMs (Carbonneau et al., 2013; Holmes, 2013; Lafay et al., 2019). However, the physical nature of PMs may not be necessary for learning, with one meta-analysis concluding that virtual (digital) manipulatives are more effective than PMs for maths learning (Moyer-Packenham & Westenskow, 2013). Literature reviews summarise the potential benefits of virtual manipulatives on early maths learning (Clements & Sarama, 2008; Tran et al., 2017).

Although PMs have also been used for teaching other subjects including reading and science, research in these domains is more limited. A review study by Trivette et al. (2012) found that book reading plus illustrations and/or PMs enhanced children's literacy skills. However, the review did not differentiate between illustrations and PMs, and very few of the studies in the review involved PMs. A meta-analysis of spatial intervention studies with children aged 0–8 years found that strategies such as hands-on exploration, visual prompts and gestural spatial training can boost children's spatial skills (Yang et al., 2020). Other reviews and meta-analyses provide evidence for the positive effects of hands-on activities for learning scientific concepts; however, most of the data are from older middle and high school students (Caglak, 2017; Schwichow et al., 2016).

Several reviews have also examined the efficacy of different forms of instruction and guidance in facilitating children's learning. Alfieri et al. (2011) compared structured versus unstructured pedagogies (see also Kirschner et al., 2006), Pyle et al. (2017) conducted a scoping review of play-based teaching approaches, and a recent systematic review and meta-analyses examined guided-play approaches in educational contexts (Skene et al., 2022). However, not all the studies reviewed focused on PMs.

The current scoping review aims to map literature evaluating educational interventions involving PMs and differs from previous research in several ways. First, a broad range of research is considered, independent of the main learning domain targeted or the pedagogical approach used. The review characterises PM research and explores similarities and differences across studies. Data related to study characteristics are summarised descriptively and quantitively in tables, and other factors of interest (e.g., type of instruction, physical engagement) are discussed qualitatively using a narrative synthesis approach. Finally, although some previous reviews have not distinguished between physical and virtual manipulatives (Bouck & Park, 2018; Lafay et al., 2019), this review specially focuses on interventions involving physical (tangible, concrete) materials (including studies comparing physical and virtual materials).

# METHOD

## Overview

The methodology was informed by Arksey and O'Malley (2005) framework for scoping reviews (see also Levac et al., 2010), and a protocol was registered with the Open Science Framework (OSF; https://osf.io/p4jk9/). The procedures for identifying, screening and summarising the literature are described in the following subsections. There were some deviations from the original plan, primarily due to the iterative process of conducting a scoping review and resource constraints.

## Identification of relevant studies

### Search strategy

Searches were conducted using six bibliographic databases that index published and unpublished (dissertations and theses) papers, including *PsycINFO* (*EBSCO*), *Child Development and Adolescent Studies* (*EBSCO*), *ERIC* (*EBSCO*), *British Education Index* (*EBSCO*), *Scopus*, and *ProQuest Dissertations & Theses*.

Search terms corresponded to three categories: (1) primary and pre-primary school age children, (2) PMs, and (3) interventions. Search terms within each category were separated by the ‘OR’ Boolean operator, and categories were separated with the ‘AND’ operator (search terms and syntax are provided in Appendix S1). Title, abstract and keyword fields were searched. The search was limited to papers published (or otherwise made available) between 2000 and 2020; no other limiters were used. Searches took place on 5 May 2020. Additional studies published after this date were also included if identified via hand search or provided by an author.

### Study screening and selection: Inclusion and exclusion criteria

The study selection procedure was conducted in accordance with the PRISMA guidelines for systematic reviews (Moher et al., 2009, 2015), adapted for scoping reviews (Peters et al., 2015; Tricco et al., 2018). See Figure 1 for an illustration of this procedure.

Codes corresponding to inclusion and exclusion criteria were created and used during the study screening phase. First, titles and abstracts off all identified reports were screened for inclusion using criteria 1–6 in Table 1. Studies were excluded if they violated any criterion, otherwise they were included for the second stage of screening if they met all criteria or if more

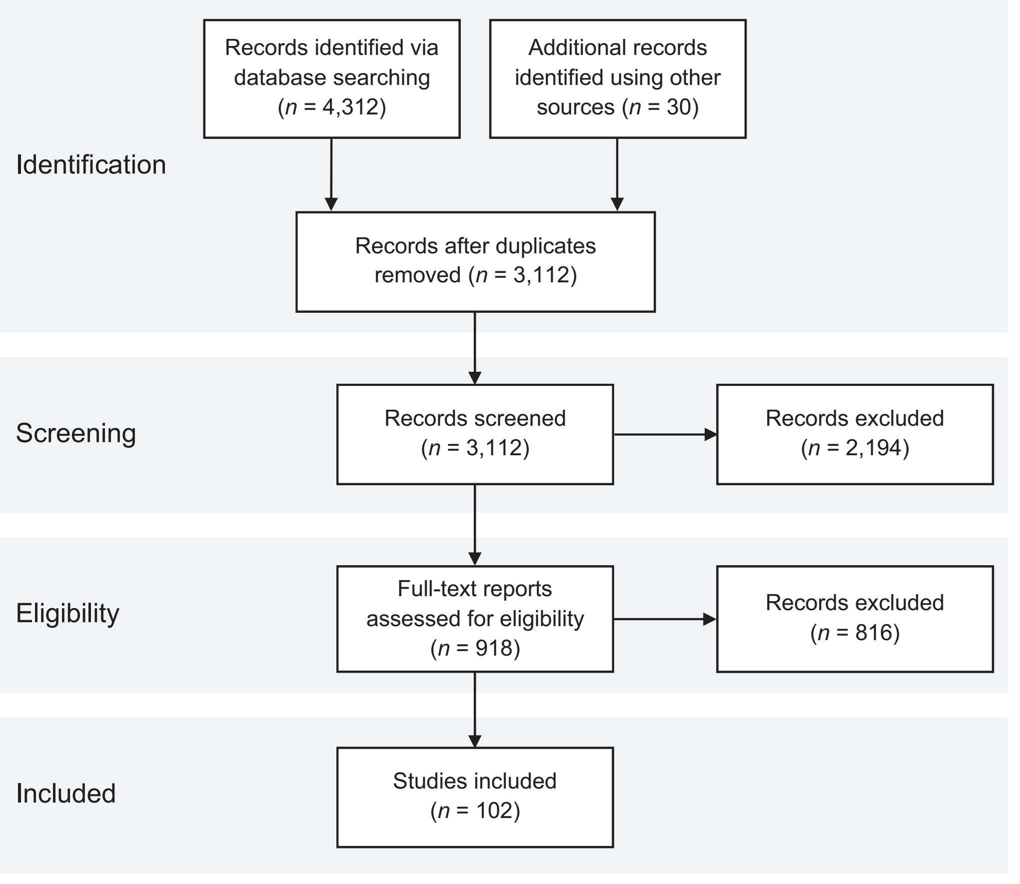


FIGURE 1 PRISMA search process flow diagram (adapted from Peters et al., 2015).

information was needed to determine eligibility. Full text screening was then undertaken on this subgroup using all codes (1–11) in Table 1. At this stage, only studies with a sample size of at least 20 participants were included. This cut-off was used to exclude studies with very small sample sizes and ensure that the number of included studies would be manageable.

Two researchers double-screened a subset of 156 (5.0%) and 46 (5.0%) reports prior to the title/abstract and full-text screening stages, respectively. This was to ensure that the eligibility criteria and corresponding guidance notes were clear and appropriate. Discrepancies were discussed and the codes were adjusted accordingly. One researcher conducted screening of all reports at both stages. Further details regarding the inclusion and exclusion criteria are provided in Appendix S1. No restrictions were placed on the type of report (e.g., published journal article, PhD thesis, conference report).

## Charting the data

### Data extraction

A descriptive-analytic method was used to guide extraction of information according to a data charting framework, provided in Appendix S1. Information relating to study location, participant characteristics, research design, intervention delivery, intervention materials and

**TABLE 1** Inclusion criteria.

| Code | Inclusion criteria |
|---|---|
| *Title and abstract screening* | |
| Publication date | 2000–2020 |
| Publication language | English |
| Sample age (mean) | 0–12 years |
| Study type | Empirical studies evaluating an intervention |
| Intervention | Educational, hands-on activities with PMs |
| Outcome | At least one clear and measurable child outcome related to learning |
| *Additional codes for full-text screening* | |
| Full publication text | Available |
| Sample size | ≥20 |
| Materials | Concrete/tangible objects |
| Data | Quantitative |
| Focus of study | At least one intervention activity in which children physically engaged with PMs and that had a clear learning goal |

*Note*: One report was published in 2021 [Tian]. Initially, a thesis was identified in the search and the first author subsequently provided a full-text journal article following its publication. Exclusions to concrete objects included items used for writing and art-based activities (e.g., drawing, painting), purely electronic or digital materials, and tangible-user-interfaces (TUIs: concrete objects used to engage with digital interfaces).

content, comparison group(s), main outcome domains, and main findings, was gathered from all reports deemed eligible for inclusion. Data extraction codes were created, and extracted data were recorded, in EPPI-Reviewer (Thomas et al., 2010).

Data extraction was carried out by one researcher. Prior to this, two researchers independently screened a subset of 10 reports (9.8%) to ensure that codes corresponding to the to-be-extracted data were clear and appropriate. Discrepancies and difficulties that arose during the process were discussed, and the codes were adjusted accordingly (codes were also adjusted iteratively throughout the data extraction process).

Where information was missing in the reports, attempts were made to contact the author(s) via email. References of studies that did not provide sufficient information to determine eligibility, and were therefore excluded, are provided in Appendix S1.

## Data synthesis

Studies were broadly categorised according to learning domains targeted and the types of PMs used. Tables summarise key study characteristics. A narrative synthesis approach was used to provide a descriptive overview of the interventions and reported findings, mapping similarities and differences across studies and identifying methodological limitations and gaps in the research. A formal scoring system was not used to assess quality of the evidence due to the large degree of heterogeneity in research designs, but key features relating to quality are summarised in tables (e.g., sample size, research design). Not all studies were included in the narrative synthesis—those deemed less relevant to the focus of the review are summarised briefly.

In-text references to the review studies are shown in square brackets, for example, *[Hull]*. Only the first author is provided, unless there are multiple reports of the same first author (or different first authors with the same name), in which case the publication year is also shown, for example, [Fisher 2013]. References for the included studies are provided in Appendix S1.

# RESULTS

## Scoping the field

### Initial mapping: Study demographics and characteristics

In total, 102 PM interventions were included in the review. Most were peer-reviewed journal articles (79.4%), with the remainder being unpublished theses or dissertations (17.7%), or other reports such as conference proceedings (2.9%).

More than half the studies included children with a mean age of 4–6 years (55.9%). Children aged 0–3 years, 7–9 years, and 10–12 years were included in 9.8%, 16.7%, and 22.6% of the intervention studies, respectively. Nine studies (8.8%) included samples of children spanning multiple age groups.

Figure 2 shows the geographical distribution of studies by the country they took place in. The interventions were overwhelmingly based in the USA (59.8%). Overall, North America accounted for 62.8% of the studies, with Europe (21.6%) and the rest of the world (15.7%) accounting for the rest.

Information provided by the World Bank (2021) was used to determine the gross national income (GNI) of the countries in which the review studies took place. They were largely conducted in high-income (88.4%) and upper-middle-income (8.7%) contexts. Notably, only 2.9% were in a lower-middle-income country and none took place in a low-income context. Note that these percentages are calculated out of a total of 103 studies, as one took place in two countries.

Table 2 summarises the distribution of studies according to several characteristics (including the setting, adult involved, research design and test time points). Most interventions took place in a school setting (77.7%). Despite this, the adult delivering the interventions was typically a researcher or experimenter (45.6%), rather than a school teacher (36.9%). This may reflect differences in the purpose of the studies: although some implemented educational

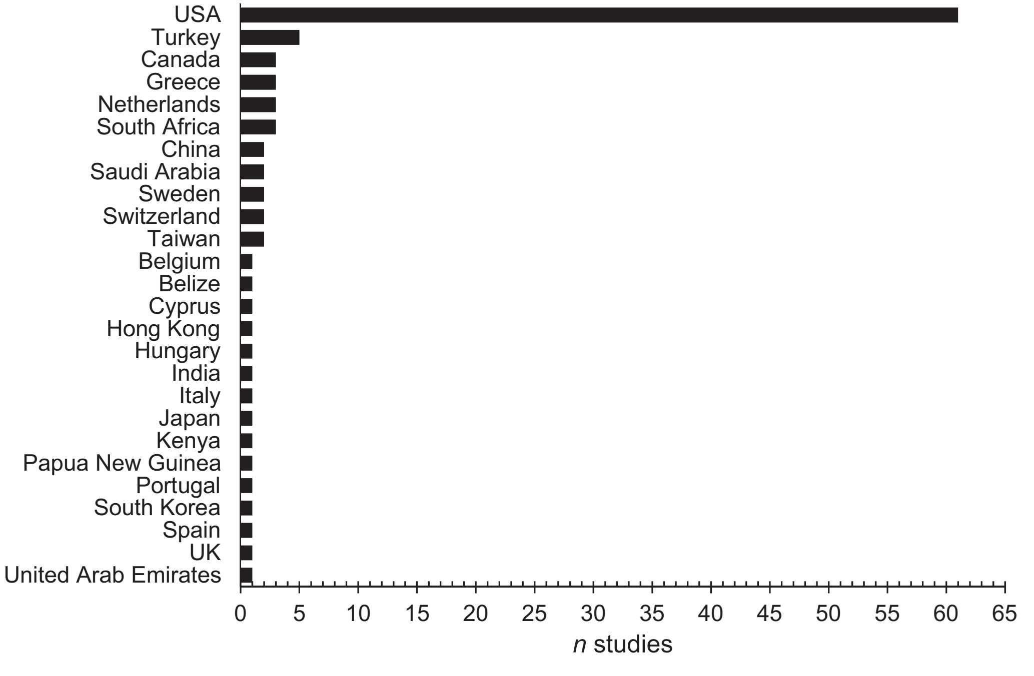


FIGURE 2 Geographical distribution of studies by country. *Note*: One study was conducted in both Kenya and South Africa.

**TABLE 2** Summary of study characteristics, including the intervention setting, adult involved, research design and test time points.

| Study characteristics | *n* studies |
|---|---|
| *Setting* | |
| School/classroom | 78 |
| Lab | 8 |
| Home | 7 |
| Childcare centre | 4 |
| School/classroom & home | 2 |
| School/classroom & lab | 1 |
| Unclear | 2 |
| *Adult involved* | |
| Researcher | 47 |
| Parent/caregiver | 11 |
| Teacher | 36 |
| Teacher & parent/caregiver | 2 |
| Other (school psychologist) | 1 |
| Unclear | 5 |
| *Research design* | |
| RCT | 61 |
| QE | 37 |
| One group | 3 |
| Unclear | 1 |
| *Test time points* | |
| Pre-post | 84 |
| Post only | 9 |
| During only | 8 |
| Pre-post intervention, post-only control | 1 |

programmes and provided teacher training to support delivery [e.g., Hull; Sophian], others—despite being conducted in an educational setting—were more aligned with lab-based experimental studies [e.g., Fisher 2013; Martin]. For example, children were taken from their classroom to a separate room for an individual or small-group session with an experimenter.

Most studies used a randomised controlled trial (RCT) design (59.4%)—debatably the 'gold standard' methodology (Hariton & Locascio, 2018), or at least a good experimental design (Grossman & Mackenzie, 2005; Lilienfeld et al., 2018), to evaluate intervention effectiveness. Finally, three interventions did not include a comparison condition, and although some studies did not gather baseline data, most assessed children at both pre- and post-test time points (83.3%).

## REVIEW OF INTERVENTIONS INVOLVING PHYSICAL MANIPUALTIVES: A NARRATIVE SYNTHESIS

The 102 studies included in the review varied substantially in terms of the learning domains targeted, materials and activities employed, and methodologies. To aid synthesis of the information extracted from the reports, they were broadly grouped into three learning domains, including: *maths and numeracy* ($n$=47), *reading and literacy* ($n$=8), and *science* ($n$=9). Thirteen studies did not correspond to the three main learning domains, instead they targeted learning and skills related to visual perception, social–emotional development, executive function, geography and play.

The studies are discussed in subsequent sections, including information about: (1) intervention materials and activities; (2) physical engagement (deemed as low [moving/touching a PM], moderate [physical manipulation/transformation, e.g., rotating or arranging PMs], or high [building/construction with PMs, or otherwise arranging/transforming them to create something new or more complex]); (3) type of instruction (child- or adult-led, e.g., free play, guided play, direct instruction); and (4) evidence relating to their effectiveness. Further details about the main outcomes and findings of each study can be found in Appendix S1.

Narrative synthesis revealed substantial variation in methodological rigour across interventions, exposing weaknesses such as small sample sizes, lack of control (or active control) groups, no baseline data, inadequate outcome/transfer measures (e.g., researcher-made, or closely tied to intervention tasks), and/or inadequate statistical analyses or reporting. Studies with strong methodologies are noted.

An additional 25 studies were identified that involved boardgames and card games. These studies were deemed less relevant due to the limited amount of physical engagement the games afforded children and are discussed in less detail.

## Maths interventions (*N*=47)

### Intervention characteristics

#### *Materials and activities*

Most of the studies included in this review focused on children's maths and numeracy, or related constructs like visual-spatial reasoning (see Table 3 for a summary of study characteristics). A range of maths concepts and skills were targeted using numerous activities and materials. Children used PMs to help solve maths problems about fractions (e.g., manipulating fraction circles, pies, tiles, blocks) [Alshehri; Aleid; Cramer; Eason; Martin; Mendiburo; Moyer-Packenham], probability (e.g., rolling dice, flipping coins) [Taylor 2001], measurement concepts such as area, volume, length and weight (e.g., filling containers) [Dennis; Sophian], proportional reasoning (e.g., interacting with magnetic strips representing volume) [Fujimura], and computation (e.g., addition, equivalent equations) [Ermakova; Mattoon; Watchorn]. Several interventions targeted children's geometry and spatial skills via activities such as shape sorting and matching, exploring shapes via touch, and solving geometric puzzles and tangrams (i.e., arranging shapes into more complex configurations, e.g., a rabbit outline) [Casey 2008b, 2008c; Fisher 2011a, 2011b, 2013; Gecu-Parmaksiz 2018, 2019; Hawes; Olkun; Thompson 2012, 2016; Verdine]. Children also used counters, toys, sticks and other small objects for counting, addition, sharing/dividing and ordering/sorting by size [e.g., Alghazo; Bennett; Horan]. Some interventions targeted multiple concepts, aiming to enhance general maths ability [Bennett; Hull; Sophian; Starkey] or involved many activities and games [Vander Heyden]. Curriculum-based interventions lasted for several weeks or months, involved numerous PMs and activities, and were integrated into, or implemented in lieu of, existing maths curricula [Bennett; Cramer; Hawes; Hull; Sophian; Starkey; Thompson 2012].

Eleven maths interventions involved block or brick play [Borriello; Boyle; Casey 2008a; Ferrara; Newman; Pirrone; Schmitt; Simoncini; Tian; Vander Heyden; Willson-Quayle]. In these studies, children typically engaged in semi-structured building activities by following

**TABLE 3** Characteristics of math intervention studies PMs ($n = 47$), including math-based materials, block building, and paper folding/origami.

| ID | Location | Sample N | Age | Research design | Setting | Model of delivery | Adult involved | N sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aleid 2015 | Saudi Arabia | 622[1] | 10–12 | RCT, pre-post | School/ classroom | Class/ pairs | Teacher | 11–20 | Fraction bars, base-10 blocks | Fraction/decimal tasks with PMs; child dyads alternated a peer tutor role | 1. PMs alone; 2. Peer tutoring alone; 3. No-intervention | Math/ numeracy |
| Alghazo 2010 | United Arab Emirates | 48 | 4–6 | QE, pre-post | School/ classroom | Class | Teacher | >20 | Numbered cubes, counters/ small toys, marbles | PM activities (counting, ordering) & multimedia content (computer visuals, audio)[2] | No-intervention | Maths/ numeracy |
| Alshehri 2017 | Saudi Arabia | 163[3] | 10–12 | QE, pre-post | School/ classroom | Class/ group | Teacher | 2–5 | Fraction bars | PMs & maths fraction problems | 1. Virtual materials; 2. No-intervention | Maths/ numeracy |
| Bennett 2000 | USA | 57 | 4–6 | QE, pre-post | Childcare centre | Group | Teacher | >20 | Shapes, counters, dominoes buttons, etc | Storytime & PMs (counting, sorting, length estimation); teacher-guided | Traditional teaching | Maths/ numeracy |
| Boakes 2009 | USA | 56 | 10–12 | QE, pre-post | School/ classroom | Class | Teacher | 11–20 | Paper | Adult-led origami-maths lessons (step-by-step instructions) | No-intervention | Visual-spatial, maths-spatial |
| Borriello 2018 | USA | 41 | 4–6 | QE, during-only | Lab | Individual | Parent/ caregiver | 1 | LEGO, puzzle | Puzzle activity; free/structured LEGO play; mothers told about the value of spatial skills | Same but mothers not given info about spatial skills | Spatial language, play-based |
| Boyle 2017 | USA | 29 | 4–6 | One group, pre-post | School/ classroom | Group | Researcher | >20 | Building blocks | Block building simple & complex structures from images (tower, castle, giraffe) | N/A (no control group) | Visual-spatial |

(Continues)

**TABLE 3** (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Burte 2017 | USA | 86 | 7–9, 10–12 | One group, pre-post | School/ classroom | Class/ group | Teacher | 6–10 | Paper | *Think3d!* programme: teacher-scaffolded origami & pop-up paper engineering | N/A (no control group) | Maths/ numeracy, visual-spatial |
| Cakmak 2014 | Turkey | 38 | 10–12 | One group, pre-post | School/ classroom | Class | Researcher | 6–10 | Paper | Adult-led origami (step-by-step instructions); class discussed geometry & maths | N/A (no control group) | Visual-spatial |
| Casey 2008a | USA | 100 | 4–6 | QE, pre-post | School/ classroom | Class/ group | Teacher | 6–10 | Building blocks | Structured block play: helping story puppet characters build a castle with predefined features | 1. Structured building, no story; 2. Regular maths class & free block play | Visual-spatial |
| Casey 2008b[4] | USA | 155 | 4–6 | RCT, pre-post | School/ classroom | Class/ group | Teacher | 6–10 | 2D & 3D geometric puzzles | Geometric puzzles & storytime with interactive elements (movements, puppets, chants) | Business-as-usual (regular maths classes) | Maths-spatial |
| Casey 2008c[5] | USA | 63 | 4–6 | RCT, pre-post | School/ classroom | Class/ group | Teacher | 6–10 | As above | As above | Geometry alone (no story) | Maths-spatial |
| Cramer 2002 | USA | 1666 | 10–12 | RCT, post-only | School/ classroom | Class/ group | Teacher | >20 | Fraction circles, chips, paper folding | Rational Number Project: PM curriculum for fraction learning | Traditional teaching (textbook & PMs to lesser extent) | Maths/ numeracy |

**TABLE 3** (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dennis 2011 | USA | 20 | 10–12 | QE, pre-post | School/ classroom | Class | Teacher | >20 | Containers (bottle, cup), materials (rice, water) | Hands-on learning of concepts like volume, area, length (e.g., filling containers) | Same as intervention without PMs | Maths/ numeracy |
| Eason 2020 | USA | 72 | 4–6 | RCT, during-only | Lab | Individual | Parent/ caregiver | 1 | Segmented toy food | Dyads used segmented toy food to explore whole & part concepts (divided food between characters in picnic story) | 1. Free play with same materials 2. Formal learning (could see but not touch PMs) | Literacy/ language |
| Ermakova 2017 | USA | 61 | 4–6 | RCT, pre-post | School/ classroom | Group | Researcher | 2–5 | Base-10 frames & tiles | Adult showed children how to use maths PMs | Same as intervention with only frames *or* tiles | Maths/ numeracy |
| Ferrara 2011 | USA | 72 | 4–6 | RCT, during-only | Lab | Individual | Parent/ caregiver | 1 | Building blocks, figurines | Parent–child block play: photos used to guide building steps & figurine placement | 1. Free play with blocks; 2. Play with pre-made structures | Spatial language |
| Fisher 2011a[6] | USA | 42 | 4–6 | RCT, post-only | Lab | Individual | Researcher | 1 | Geometric shape cards | Children 'discovered' the 'secrets' (properties) of shapes via touch/tracing | 1. Didactic instruction (no touch); 2. Reading | Maths/ numeracy |

(Continues)

**TABLE 3** (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fisher 2011b[7] | USA | 38 | 4–6 | RCT, post-only | School/ classroom | Individual | Researcher | 1 | Geometric shapes & sticks | As above plus additional activity (making new shapes with sticks) | 1. Didactic (no touch); 2. Free play with shapes/sticks | Maths/ numeracy |
| Fisher 2013[8] | USA | 60 | 4–6 | Unclear, post-only | School/ classroom & lab | Individual | Researcher | 1 | As above | As above | As above | Maths/ numeracy |
| Fujimura 2001 | Japan | 76 | 7–9 | RCT, pre-post | School/ classroom | Individual | Researcher | 1 | Magnetic strips | 'Mixing' blue (water) & orange (juice) magnet strips & estimating 'concentration' (proportional reasoning) | 1. Worksheet (same problems, no PMs) 2. Non-proportional problems (no PMs) | Maths/ numeracy |
| Gecu-Parmaksiz 2018, 2019[9] | Turkey | 72 | 4–6 | RCT, pre-post | School/ classroom | Group | Teacher | 2–5 | Shape cards & geometric solids | Examining & classifying shapes using cards & blocks | Virtual manipulatives via tablet computer | Visual-spatial, maths/ numeracy |
| Hawes 2017 | USA | 65 | 4–6 | QE, pre-post | School/ classroom | Class | Teacher | >20 | Pentominos, tiles, geometric shapes, cubes, & others | PM spatial geometry tasks; design challenges (e.g., making keys, garden patios) | Environmental science Inquiry learning (gravity, weather, lifecycles) | Maths/ numeracy, maths-spatial, receptive & spatial language |
| Horan 2018 | USA | 165 | 4–6 | RCT, pre-post | School/ classroom | Group | Researcher | 2–5 | Coins and paper-printed coin strips | Counting PM numbers 1–10 & placing them on a board (adult-guidance varied by group) | Four groups in study (all with different levels of adult guidance) | Maths/ numeracy |

TABLE 3 (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hull 2018 | Belize | 6628 | 4–6, 7–9, 10–12 | RCT, pre-post | School/ classroom | Class/ group | Teacher | >20 | Geoboards, geometric solids, flash cards, counters | Curriculum programme: teachers trained on the use of PMs & inquiry-based hands-on maths activities | Traditional maths teaching & alternative teacher training not involving math or PMs | Maths/ numeracy |
| Krisztián 2015 | Hungary | 37[10] | 10–12 | RCT, pre-post | School/ classroom | Group | Researcher | 6–10 | Paper | Origami training: children with maths difficulties folded paper patterns & decorated models | No-intervention (children with & without maths difficulties) | Maths/ numeracy, visual-spatial |
| Martin 2012 | USA | 21 | 7–9 | RCT, during-only | School/ classroom | Individual | Researcher | 1 | Tiles | PMs used for fraction learning (e.g., represent 1/3 of 6); adult provided feedback & hints | Same as intervention but using pictures instead of PMs | Maths/ numeracy |
| Mattoon 2015 | USA | 24 | 4–6 | QE, pre-post | School/ classroom | Group | Teacher | 11–20 | Cubes, dice, toy counters | Maths tasks with PMs; teacher provided feedback | Virtual (tablet) materials with automatic feedback | Maths/ numeracy |
| Mendiburo 2011 | USA | 67 | 10–12 | RCT, pre-post | School/ classroom | Unclear | Researcher | 6–10 | Paper fraction strips | Fraction activities & games with PMs constructed with paper | Virtual fraction activities/ materials | Maths/ numeracy |
| Moyer-Packenham 2013 | USA | 350[11] | 7–9 | RCT, pre-post | School/ classroom | Class | Teacher | 11–20 | Fraction pies & tiles | PMs used with worksheet fraction problems (first modelled by teacher) | Virtual manipulatives (tablet computer) | Maths/ numeracy |

(Continues)

TABLE 3 (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Newman 2016 | USA | 28 | 7–9 | QE, pre-post | Lab | Individual/ pairs | Researcher | 2–5 | Building blocks, card game | *Blocks Rock!* commercial game; quickly building target structures | Commercial word boardgame (Scrabble) | Visual-spatial |
| Olkun 2003 | Turkey | 93 | 10–12 | QE, pre-post | School/ classroom | Unclear | Unclear | 1 | Wooden tangram puzzles | Children solved tangram puzzles with wooden shapes | 1. Virtual puzzle 2. Business-as-usual | Maths-spatial, visual-spatial |
| Pirrone 2018 | Italy | 33 | 4–6 | RCT, pre-post | School/ classroom | Class | Teacher | >20 | LEGO | LEGO used build with & learn maths operations | Business-as-usual (maths classes) | Maths/ numeracy, visual-spatial, fluid intelligence |
| Schmitt 2018 | USA | 59 | 4–6 | RCT, pre-post | School/ classroom | Group | Researcher | 11–20 | Building blocks | Semi-structured block play, guided by prompts & images | Business-as-usual | Maths/ numeracy, executive function |
| Simoncini 2020 | Papua New Guinea | 45 | 4–6 | QE, post-only | School/ classroom | Class | Teacher | >20 | DUPLO, MegaBlocks, wooden blocks | Teachers received blocks (for learning maths/ numeracy), plus some free play building | Business-as-usual (no blocks) | Maths/ numeracy |
| Sophian 2004 | USA | 123 | 0–3 | QE, pre-post | School/ classroom & home | Class/ group/ individual | Teacher & parent/ caregiver | >20 | Counters, tiles, scales, containers, board/card games, shapes, puzzles | Curriculum with weekly themes (shapes/ geometry, weight, volume/ capacity); PM activities (size sorting, fill container, calculate area with tiles) | 1. Literacy curriculum 2. No-intervention | Maths/ numeracy |

**TABLE 3** (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Starkey 2004 | USA | 163 | 4–6 | QE, pre-post (intervention), post-only (control) | School/ classroom & home | Class/ group/ individual | Teacher & parent/ caregiver | >20 | Shapes, counters, sticks, cards, & others | Pre-K curriculum: teacher-guided tasks about patterns, shapes, numbers & set size, arithmetic, measurement (some computerised or parent-guided) | No-intervention (successive cohort design) | Maths/ numeracy |
| Taylor 2001 | USA | 66 | 10–12 | QE, pre-post | School/ classroom | Class/ group | Researcher | 2–5 | Coins, dice, cubes, spinners, marbles | Activities with PMs about probability & chance (e.g., tossing coins, rolling dice, & making predictions) | 1. Computer materials; 2. PMs & computer materials; 3. Traditional teaching | Maths/ numeracy |
| Taylor 2013 | USA | 39 | 10–12 | QE, pre-post | School/ classroom | Class/ group | Researcher | 6–10 | Paper | *Think3d!* programme: origami & pop-up paper engineering; children made models with diagrams/ instructions | No-intervention | Visual-spatial |
| Thompson 2012 | USA | 157 | 4–6 | QE, pre-post | School/ classroom | Class | Teacher | >20 | 3D geometric shapes | Activities with 3D shapes (stacking, sliding, rolling, making complex objects, counting faces/ edges) | 1. Multimedia (shape videos); 2. PMs & multimedia; 3. No-intervention | Maths-spatial |

(Continues)

TABLE 3 (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Thompson 2016 | USA | 61 | 7–9 | QE, pre-post | School/ classroom | Class/ group | Teacher | 2–5 | Wooden tangram puzzles | Tangram puzzles; plus group discussion & worksheets | 1. Virtual puzzle 2. Multimodal (physical & virtual) | Maths/ numeracy, visual-spatial |
| Tian 2021 | China | 46[12] | 0–3 | QE, pre-post | School/ classroom | Group | Researcher | 6–10 | Wooden blocks | Structured block building: copying pre-built models | Drawing intervention | Visual-spatial, social-emotional |
| Vander Heyden 2017 | Netherlands | 140 | 7–9 | QE, pre-post | School/ classroom | Group | Researcher | 2–5 | Wooden blocks, other spatial toys, marble run | Spatial training: playful activities & commercial games (construction, object transformation) | Business-as-usual | Visual-spatial |
| Verdine 2019 | USA | 60 | 0–3 | RCT, during-only | Lab | Individual | Parent/ caregiver | 1 | Geometric shapes | Parent–child dyads used standard (e.g., triangle) & alternate shape (e.g., long, thin triangle) PMs | 1. PM standard shapes; 2. Virtual standard shapes | Spatial language |
| Watchorn 2011 | Canada | 273 | 7–9, 10–12[13] | RCT, pre-post | School/ classroom | Individual | Researcher | 2–5 | Cylindric wooden blocks & trays | Adult-directed; children put blocks in trays to match maths equivalence problems | 1. No PMs (same maths problems); 2. Maths instruction on unrelated topic | Maths/ numeracy |
| Willson-Quayle 2001 | USA | 61 | 4–6 | RCT, pre-post | School/ classroom | Individual | Researcher | 1 | DUPLO | Adult-scaffolded block play | 1. Adult-directed block play 2. Free play | Visual-spatial, social-emotional |

**TABLE 3** (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Yuzawa 2002 | USA | 24 | 4–6 | RCT, during-only | School/ classroom | Individual | Researcher | 2–5 | Paper | Origami & size comparison: adult-led folding steps; stopped to correct children's mistakes | Size comparison tasks only | Maths-spatial |

*Note:* For inclusion in the review, a threshold of ≤20 was used for the child sample *N* (based on *N* included in analyses). The mean age of the sample was coded according to four categories (0–3, 4–6, 7–9, 10–12; i.e., it does not represent the age range). *N* sessions was coded according to five categories (1, 2–5, 6–10, 11–20, >20). 'During-only' refers to outcome data being collected *during* the intervention activities only (i.e., findings are not based on pre- or post-data). [1,3]Male-only samples (due to gender-segregation rules in Saudi Arabian schools). [2]Unclear how much of the intervention involved PM versus other media. [4,5]Casey 2008b and 2008c are different studies in one paper. [6,7,8]Fisher 2011a and 2011b have different participants; Fisher 2013 has the same sample as Fisher 2011b with additional participants. [9]Gecu-Parmaksiz 2018 and 2019 have been grouped as they report on the same study and sample. [10]Female-only sample. [11]Total sample split between third ($n = 156$) and fourth grade ($n = 194$) pupils, analysed separately. [12]65 children completed the study (had post-test data) but only 46 were included in the analysis (a subsample matched on several variables like age, gender, baseline block-building skills). [13]Sample recruited from second and fourth grade classes. Children selected for the intervention based on pre-test scores (children who failed equivalence problems).

Abbreviations: QE, quasi-experimental; RCT, randomised controlled trial.

step-by-step instructions or recreating example models [e.g., Ferrara; Newman; Schmitt], though some included additional activities (e.g., addition) [Pirrone; Simoncini]. Six studies involved origami (paper folding), in which children transformed 2D paper sheets into 3D objects like geometric shapes or animals [Boakes; Burte; Cakmak; Krisztián; Taylor 2013; Yuzawa].

### *Physical engagement*

Levels of physical interaction with maths materials differed across intervention activities. Block building/construction [Borriello; Boyle; Casey 2008a; Ferrara; Newman; Pirrone; Schmitt; Simoncini; Tian; Vander Heyden; Willson-Quayle] and origami [Boakes; Burte; Cakmak; Krisztián; Taylor 2013; Yuzawa] had high demands. In geometry activities, children typically engaged in moderate physical manipulation, such as arranging, combining, flipping and rotating materials to form novel or target patterns and shapes [Casey 2008b, 2008c; Hawes; Hull; Olkun; Thompson, 2016], but in some tasks, physical interaction was minimal, limited to touching or tracing shapes [Fisher 2011a, 2011b; Verdine]. Most of the remaining interventions had low physical interaction, with merely touching or moving counters and small objects in counting and fraction tasks [e.g., Horan; Martin]. Determining physicality was at times challenging; in multimodal interventions, for instance, it was unclear how much children engaged with PMs versus computer- or picture-based materials [e.g., Alghazo].

Physical engagement varied between comparison conditions in some studies. Four studies compared guided and free play (both with PMs) to direct instruction (children could see but not touch the PMs) [Eason, Fisher 2011a, 2011b, 2013], and one compared learning with PMs versus pictures [Martin]. Nine compared physical and virtual (computerised) manipulatives, in which the *modality* of materials varied between conditions, but the learning content (maths concept) and types of materials remained constant; children classified concrete or digital geometric shapes [Gecu-Parmaksiz; Verdine], solved physical (wooden) or digital (tablet-based) tangram puzzles [Olkun; Thompson, 2016], solved fraction problems with physical or virtual fraction circles, pies and tiles [Alshehri; Mendiburo; Moyer-Packenham], learned about probability with real or computer-simulated coins and dice [Taylor 2001], or used a range of physical or virtual materials in computational tasks [Mattoon]. These comparisons may provide mechanistic insight into impact of physical, hands-on interaction with PMs on maths learning.

### *Type of instruction*

Many of the maths interventions were adult-directed [Alshehri; Boakes; Cakmak; Cramer; Dennis; Ermakova; Fujimura; Horan; Hull; Krisztián; Martin; Mattoon; Moyer-Packenham; Olkun; Taylor 2001; Thompson 2012; Watchorn; Yuzawa]. Although some used terms like *scaffolded learning* and *adult guidance* [e.g., Ermakova; Thompson, 2016], or manipulated the level of adult guidance between conditions [Horan], children's agency (and physical engagement with materials) was limited due to the highly structured nature of the tasks. Typically, children solved maths problems with task-specific PMs following a demonstration, or followed explicit step-by-step paper-folding instructions.

Fifteen studies were explicitly described as guided play interventions, or included some variation of the term, like *scaffold*, *support* or *assist*, in relation to an adult's role in a playful task [Bennett; Borriello; Casey, 2008a, 2008c; Ferrara; Eason; Fisher 2011a, 2011b, 2013; Hawes; Schmitt; Sophian; Starkey; Tian; Vander Heyden; Willson-Quayle]. Five of these involved block construction play, incorporating elements of guided play, including a playful storytelling context (children helped ‘King’ and ‘Queen’ puppet characters to build their castle) [Casey 2008a], adult guidance such as questions and prompts (e.g., *Build your favourite number*) [Pirrone; Schmitt; Willson-Quayle], and joint parent–child play [Borriello].

Playful approaches also incorporated other types of PMs alongside adult scaffolding. Children learned about *whole* and *parts* by sharing segmented toy food between characters in a picnic story [Eason], pretended to be *detectives* discovering the *secrets* (physical properties) of shapes [Fisher 2011b, 2013], engaged in hands-on discovery-based learning (e.g., filling containers with various materials to learn about concepts like volume and capacity) [Dennis; Sophian], and took part in an origami and pop-up paper engineering programme (*Think3d*!) that required children to visualise, plan and construct 3D paper models [Burte; Taylor 2013]. Maths activities were sometimes embedded within a playful storytelling context. Two studies evaluated a playful geometry intervention that incorporated a storytelling dragon-puppet to motivate children through a meaningful narrative context; children worked on maths challenges (puzzle-based tasks) collaboratively—'helping' characters in the story (e.g., making a dragon collage using triangle PMs) [Casey 2008b, 2008c]. Similarly, another intervention incorporated children's literature and story-related PMs into maths lessons (e.g., toy mice, cat counters, buttons) [Bennett].

Direct instruction was used more often in studies with relatively older children: $n$ studies = 0 (0–3 years), 6 (4–6 years), 5 (7–9 years), and 10 (10–12 years) (*note*: samples in two studies spanned multiple age brackets). Play-based maths interventions typically had relatively younger samples of children: $n$ studies = 3 (0–3 years), 18 (4–6 years), 4 (7–9 years), and 2 (10–12 years) (*note*: one study's sample spanned two age brackets).

### *Theoretical perspectives*

Many studies targeting maths outcomes referenced the concrete-to-abstract approach, and/or Piaget's and Bruner's developmental theories in their theoretical framework or background [Aleid; Alghazo; Alshehri; Bennett; Cramer; Dennis; Ermakova; Fisher 2011a, 2011b, 2013; Gecu-Parmaksiz; Horan; Hull; Martin; Mattoon; Moyer-Packenham; Sophian; Starkey; Taylor 2001; Thompson 2012]. Some studies acknowledged that solely relying on PMs for learning is insufficient, and that accompanying activities and/or providing guidance on how to use the materials is crucial for children to gain conceptual understanding (i.e., to make meaningful connections between concrete objects and the abstract maths concepts they represent) [e.g., Dennis; Martin].

## Evidence relating to effectiveness

Interventions were evaluated on a range of maths and numeracy outcomes, including fractions, volume and capacity, symbolic and non-symbolic magnitude comparison, counting, probability and general maths attainment. Improvements in children's maths, spatial and shape talk, as well as their visual-spatial reasoning (mental rotation, spatial perception, visual-spatial geometry), were also assessed. Effectiveness trials of curriculum-based programmes revealed the most compelling evidence for the positive impact of PM interventions on children's maths learning.

A large-scale study in Belize compared a maths curriculum with PMs to regular maths instruction. Intervention teachers were trained to incorporate PMs and inquiry-based hands-on activities into maths lessons, whereas control teachers received training about character development and positive discipline [Hull]. Maths instruction in developing countries like Belize is typically teacher-directed, with maths concepts being taught using abstract (symbolic) representations, which can be difficult for children to learn and apply to novel problems [Hull]. Instead, a child-centred and low-cost intervention, which incorporated PMs that could easily be fabricated at home/school and adult (teacher) guidance, was implemented. Intervention effectiveness was assessed using a robust methodology, comprising an RCT design, pre- and post-outcome measures, and a large sample ($N$ = 6628) of primary-age pupils spanning eight school grades (aged 5–12 years). Hierarchical linear (multi-level) modelling accounted for clustering at the pupil-, teacher- and school-level, and controlled for potential group differences in baseline scores. The analysis revealed that intervention children outperformed controls on age-appropriate maths achievement tests, and positive effects were associated with higher levels of teacher implementation (intervention fidelity). The findings prompted a nationwide rollout of the programme.

Pre-schoolers (aged 2–4 years) who participated in a maths curriculum that incorporated a range of hands-on activities and materials, such as sorting objects by size, filling containers and arranging shapes, performed better on maths measures than both passive and active (literacy curriculum) after accounting for their baseline scores [Sophian]. Similarly, 4-year-old children who engaged in a pre-kindergarten classroom- and home-based maths curriculum with playful PM activities, such as sharing toy bananas between monkeys, making shapes and arranging animal cards by set size, outperformed passive controls on a maths measure [Starkey]. Furthermore, intervention children from middle-income families outperformed low-income children at pre- and post-test, but lower-income children showed greater gains. Although maths curriculums using PMs show promise, improvements may be due to increased maths exposure rather than PMs themselves, as comparisons were made to passive controls or a non-maths (literacy) curriculum.

Curriculum-based studies comparing learning of the same (or similar) maths content with or without PMs demonstrated that PM-based activities benefited volume and capacity learning in 10-year-olds [Dennis], fraction learning and retention in 9- to 11-year-olds [Cramer],and counting skills in 5-year-olds [Alghazo]. However, this research is limited by the absence of pre-test data [Cramer] and lack of clarity about much of the intervention involved in PMs versus computerised media [Alghazo]. Three additional single- and two-session studies (non-curriculum-based) investigated the impact of solving the *same* maths problems (related to proportional reasoning, fractions or equivalence) with or without PMs in 7- to 10-year-olds (magnetic strips, fraction tiles, and blocks vs. paper-and-pencil activities/worksheets), but no group differences were found [Fujimura; Martin; Watchorn].

Other curriculum-based PM maths interventions yielded null or inconclusive results. There were no group differences in maths abilities among children aged 3–4 years who engaged in teacher-scaffolded maths tasks with storytelling and PMs versus traditional instruction [Bennett]. Another study found that while children aged 6–7 years who received maths instruction with PMs or multimedia/videos improved more than controls (traditional teaching) in geometry and visualisation skills, no other group differences were observed [Thompson 2012]. A curriculum-based spatial geometry programme led to selective benefits in the visual-spatial geometry scores of 5-year-olds when compared to an inquiry-based control approach on scientific topics [Hawes]. However, although statistical interactions indicated greater gains for the intervention group in mental rotation, spatial language and symbolic (number) magnitude comparison, post hoc pairwise comparisons were either not conducted or showed no significant effects. Additionally, there were no group differences for other maths (non-symbolic magnitude comparison, number knowledge) or language (receptive vocabulary) measures.

Most of the nine studies comparing physical and virtual manipulatives found that PMs were no better than digital materials for improving maths skills related to concepts such as fractions, probability and geometry in younger (4–5 years) [Gecu-Parmaksiz; Mattoon] or older (8–11 years) children [Alshehri; Mendiburo; Moyer-Packenham; Olkun; Taylor 2001] or visual-spatial skills [Gecu-Parmaksiz; Thompson, 2016]. In fact, two studies found that children who used virtual materials outperformed those who used PMs [Gecu-Parmaksiz; Mendiburo]. These effects may be due to the automated nature of computerised activities, which can provide individualised instructions and feedback, whereas teachers must monitor and guide children's use of PMs. The self-paced nature of computerised activities also allows children to progress at their own speed, meaning children using virtual materials completed more activities and had more practice with maths problems [Mendiburo]. In another study, young children (2–3 years) who used standard and alternative PM shapes produced more spatial talk than those who only used standard physical or virtual shapes [Verdine].

Studies that examined varying levels of adult guidance, child agency and physical engagement with PMs produced mixed outcomes. Two studies compared guided play, self-directed play and didactic instruction with the same PM shapes, where in the latter, children were only allowed to see but not touch the shapes. Guided play improved 4-year-old children's shape sorting more than the other conditions [Fisher 2011b; Fisher 2013] and enhanced performance on an embedded shapes task compared to free play [Fisher 2011b]. However, in another study by the same authors, no differences were found between guided play and didactic instruction on an embedded shapes task, and both methods improved shape sorting more than reading [Fisher 2011a]. Another study found that children (aged 4–5 years) who participated in parent-guided play, which involved reading a story and manipulating segmented toy food, produced more maths talk than those in a free play condition [Eason]. Additionally, a formal learning approach with no hands-on interaction led to more maths talk than both other conditions. The mixed and inconclusive results of these guided play studies may be due to low intervention intensity (single-sessions) and lack of pre-post designs (data were only gathered during or post intervention).

Selective benefits were reported following a playful storytelling geometry intervention to a triangle task with familiar shapes (same type of triangles as the intervention activity) and a tangram task with novel shapes [Casey 2008b; 2008c]. Intervention children (aged 5–6 years) outperformed geometry-only [Casey 2008c] and passive controls [Casey 2008b] on the triangle task and had greater gains on the tangrams task compared to geometry-only [Casey 2008b] but not passive controls [Casey 2008c]. Furthermore, girls benefited more than boys from the two geometry interventions, regardless of whether they also received the storytelling element.

A study comparing four intervention conditions in which 5-year-old children used coin-based PMs with varying degrees of adult guidance, found no differential impact on children's counting scores [Horan]. In others, PMs (fraction bars, base-10 blocks) plus peer tutoring improved 10- to 11-year-olds' maths skills more than PMs alone or regular teaching [Aleid], and using one or multiple types of PMs (e.g., base-10 frames or base-10 frames and tiles) did not impact 6- to 7-year-olds' likelihood of utilising a base-10 addition strategy [Ermakova].

Nine block play studies assessed spatial talk or spatial ability outcomes. Children (aged 4–5 years) who engaged in parent-guided block play produced more spatial talk than controls who played freely [Borriello; Ferrara]. These effects are likely due to adult supervision, not PM engagement, as studies did not compare block play to PM-free condition. Structured block building interventions improved visual-spatial reasoning more than regular teaching plus free play with blocks [Casey 2008a] or drawing [Tian] in 3- to 6-year-olds, and both scaffolded and adult-directed block play, but not free-play, increased 4- to 5-year-old children's block-building skills [Willson-Quayle]. Children's block play was also associated with increased functional activity in brain regions implicated in spatial processing [Newman]. However, gain scores in mental folding [Vander Heyden] and rotation [Casey 2008a; Newman; Vander Heyden] did not differ between groups (children aged 5–9 years). Although there were further reported improvements to children's visual-spatial reasoning, transformation and perspective-taking skills, findings were limited by methodological shortcomings, including no comparison group [Boyle], no accounting for group differences in baseline scores [Pirrone; Vander Heyden] and results based on post hoc analyses, despite there being no group difference in gain scores [Newman].

The results of three studies investigating the impact of block building on maths and numeracy skills were mixed. One study found that guided block play improved maths scores of 9-year-olds more than traditional teaching [Pirrone], while another found that 6-year-old children who received blocks showed selective improvements in certain areas of maths compared to those without blocks (backward number sequence and arithmetic strategies, but not subitising, number identification or forward number sequence) [Simoncini]. However, this study did not have baseline data. The third study, involving children aged 3–5 years, failed to show any benefits to several maths outcomes (numeracy, shape recognition, maths language), but some positive findings were mediated by parental education [Schmitt].

Evidence that paper-folding and origami interventions improve children's maths skills was also mixed. Maths scores of children (aged 11–12 years) in an origami programme improved more than those of passive controls—however, this finding was based on an interaction effect that was not followed up with pairwise comparisons [Krisztián]. Another study found marginal gains for older (grades 5–6; aged 10–12) but not younger (grades 3–4; aged 8–10) children who participated in the *Think3d*! paper engineering programme; however, the study lacked a control group [Burte]. Intervention-related improvements were also reported to size comparison (5- to 6-year-olds) [Yuzawa], but not geometry measures (12-year-olds) [Boakes].

Four studies revealed that interventions utilising origami techniques had a positive impact on children's (aged 8–12 years) spatial visualisation and transformation abilities (based on tasks such as mental rotation, mental knotting and mental paper folding) [Burte; Cakmak; Krisztián; Taylor 2013]. However, these studies were limited by a lack of a control group [Burte; Cakmak] and results that were determined only by *t*-test comparisons [Krisztián; Taylor 2013]. Some null effects were also reported [Boakes; Burte; Taylor 2013].

### Summary

There was evidence that PM maths interventions, using both didactic and play-based methods, can enhance children's performance on maths and spatial outcomes. Curriculum-based programmes yielded the most promising findings, demonstrating that intervention children outperformed controls on tests of maths achievement [e.g., Dennis; Hull; Sophian; Starkey], and in one case, gains were found to be mediated by intervention fidelity [Hull]. A noteworthy study was the large-scale trial conducted in Belizean schools (a lower-middle-income context), which employed a robust methodology [Hull]. Studies have also indicated that block-building can benefit children's learning across multiple areas, including spatial language, spatial reasoning and maths. However, findings were mixed, with some studies reporting null or inconclusive results. This is in part due to methodological differences across studies, which make it difficult to draw conclusions about the critical intervention components that foster maths learning. Furthermore, most studies comparing physical and computerised activities found that PMs were no better or worse than their virtual counterparts, suggesting that the physical nature of the task may not be crucial.

## Reading- and literacy-based interventions [*N* = 8]

### Intervention characteristics

#### *Materials and activities*

Table 4 summarises the study characteristics of the reading and literacy PM interventions. In five interventions, children engaged in a joint reading activity with an adult (researcher or teacher) and played with story-relevant figurines and small toys or props [Biazak; Dickinson;

**TABLE 4** Characteristics of reading and literacy PM intervention studies ($n=8$).

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biazak 2010 | USA | 56 | 4–6 | RCT, pre-post | Childcare centre | Individual | Researcher | 1 | Figurines/ toy props | Joint reading (zoo story) & play with related toys (e.g., people, monkey, tree, elephant); children moved toys to enact characters & their actions | Listening-only condition (no PMs) | Memory (verbal) |
| Cavanaugh 2017 | USA | 41 | 4–6 | QE, pre-post | School/ classroom | Group | Teacher | 11–20 | Small toys/ items | Following a teachers' example, children used phonics-related items (e.g., toy tiger for *t*) & made their own games (e.g., sorting, storytelling) | Teacher-directed instruction with the same materials. | Literacy/ language |
| Cobb 2001 | USA | 59[1] | 4–6, 7–9[2] | RCT, pre-post | School/ classroom | Individual | Researcher | 11–20[3] | Toys/ props | Joint reading with PMs that hinted comprehension strategies (e.g.,toy car = *read on* to see if rest of the sentence provides a clue to word meaning); & some PM free play | Business-as-usual (regular literacy classes) | Literacy/ language |

(Continues)

**TABLE 4** (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dickinson 2019 | USA | 227 | 4–6 | RCT, pre-post | School/ classroom | Group | Teacher | 11–20[4] | Figurines/ toy props | Read-play-learn: after book reading teachers re-enacted a story with PMs; children played with PMs & teachers focused dialogue on target words (e.g., open-ended questions) | Reading without additional play sessions | Literacy/ language, social-emotional |
| Han 2010 | USA | 49[5] | 4–6 | RCT, pre-post | School/ classroom | Pairs | Researcher | >20 | Toy props | EIVP & play: joint book reading; an adult modelled actions relating to target words with PMs; followed by adult-guided (modelling, co-play, following child's lead) play in which children enacted target words like 'baking' with props | Reading with PMs but no additional play episodes | Literacy/ language |
| Lane 2009 | USA | 100 | 4–6 | RCT, pre-post | School/ classroom | Individual | Researcher | >20 | PM letters | Early literacy intervention (full programme); adult-scaffolded reading, PM letter activity, & writing | 1. No writing; 2. No PMs; 3. No other sources; 4. No-intervention | Literacy/ language |

**TABLE 4** (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Toub 2018 | USA | 249 | 4–6 | RCT, pre-post | School/ classroom | Group | Researcher | 6–10 | Figurines/ toy props | Book reading plus adult-guided play with story-relevant PMs (child-led, adult: co-play, modelling, used target words at naturally occurring moments) | 1. Reading & free play (no adult guidance) 2. Reading & adult-directed play | Literacy/ language |
| Weisberg 2015 | USA | 154 | 4–6 | RCT, pre-post | School/ classroom | Group | Researcher | 6–10 | Figurines/ toy props | Joint reading & play with story-relevant PMs; adult-guided (encouraged children to enact story with PMs, open-ended questions, target words); *see comparison to right for more information* | Two groups read & played with either *realistic* (farm) or *fantasy* (dragon) themed materials | Literacy/ language |

*Note:* For inclusion in the review, a threshold of ≤20 was used for the child sample *N* (based on *N* included in analyses). The mean age of the sample was coded according to four categories (0–3, 4–6, 7–9, 10–12; i.e., it does not represent the age range). *N* sessions was also coded according to five categories (1, 2–5, 6–10, 11–20, >20). 'During-only' refers to outcome data being collected *during* the intervention activities only (i.e., findings are not based on pre- or post-data). [1]Children were typically developing (no developmental diagnosis) but identified the 'lowest performing students in each grade' by teachers. [2]Grades one to three (ages 6–7, 7–8, 8–9 years, respectively) were analysed separately. [3]Unclear if PMs were incorporated into all intervention sessions. [4]>20 intervention sessions, but not all of them involved PMs. [5]Children from low-income families.

Abbreviations: EIVP, explicit instruction vocabulary protocol; QE, quasi-experimental; RCT, randomised controlled trial.

Han; Toub; Weisberg] (e.g., re-enacting a story by pretending to bake a cake [Biaszak; Dickinson; Han]). Adults facilitated language learning or comprehension during play sessions with PMs by incorporating target vocabulary, elaborating on children's talk, asking closed- and open-ended questions, and/or using definitions [Dickinson; Toub; Weisberg]. Three studies incorporated a range of PMs and activities: small toys and objects were used to prompt comprehension strategies during reading [Cobb] or represented phonemes in child-invented literacy games [Cavanaugh], and PM letters were used in phoneme segmenting tasks [Lane].

#### *Physical engagement*

Children's levels of physical engagement with PMs were deemed moderate (manipulating items to act out a scenario) to low (touching or moving items) in the reading and literacy studies. They typically used small toys and figurines to enact scenes or actions from a story, but the nature of the props and activities limited the amount of physical manipulation that was possible.

#### *Type of instruction*

Five studies used guided play, with varying degrees of adult guidance and child agency. The most noteworthy implementation of guided play was observed in two studies. In one, an adult supported children as they played with story-relevant PMs by following their lead, engaging in co-play, asking questions, and teaching new words in a natural and interactive manner [Toub]. In the other, children were given freedom to work with their peers to create their own games using PMs, focusing on phonics [Cavanaugh]. Other studies involving adult-guided play-based learning afforded children relatively less agency within their play. For example, an adult modelled actions for target words from a story, then encouraged children to enact target words during play with toys and props [Dickinson; Han; Weisberg]. Other interventions involved prescribed, adult-directed activities [Biazak; Cobb; Lane].

#### *Theoretical perspectives*

Studies exploring the benefits of hands-on activities with PMs for literacy and language were informed by theories such as Bruner's enactive-iconic-symbolic learning modes, Piaget's theory of concrete-to-abstract thinking, Vygotsky's ideas that children construct meaning through physical interaction and play, and the idea that learning is embodied and closely tied to physical context [Biazak; Cavanaugh; Han].

## Evidence relating to effectiveness

Assessed learning outcomes included: early literacy skills, reading, receptive vocabulary, expressive vocabulary, memory retention for story content and self-regulation. Research aims varied across studies, meaning that different comparison groups were used: some manipulated the level of instruction (e.g., guided play vs. direct instruction; [Cavanaugh; Han]) and/or the inclusion of PMs (e.g., reading with vs. without PMs; [Biazak]), whereas others manipulated neither of these task features [e.g., Weisberg]. This limits the conclusions that can be drawn regarding the relative importance of PMs and/or the level of adult guidance and child agency. Although all the studies employed an experimental pre- and post-test design, their analytic methods differed: some used more rigorous techniques (e.g., controlling for potential variations in pre-test scores between groups and/or nesting in classrooms; [Dickinson; Biazak; Lane; Toub]), whereas others did not [e.g., Cobb; Han].

Evidence that literacy-rich guided play interventions promote 3- to 6-year-old children's literacy and vocabulary learning was mixed. One study found that both guided and directed play with PMs led to improvements in receptive and expressive vocabulary when compared to free play with PMs, but there were no differences between the guided and directed groups [Toub]. In contrast, other studies found that guided play with PMs improved children's early literacy skills [Cavanaugh] and receptive (but not expressive) vocabulary [Han] more than adult-directed instruction with PMs [Cavanaugh]. As PMs were included in all the intervention conditions of these studies, their relative importance for the intervention-related effects are uncertain. Two studies compared reading interventions with and without PMs. Children who used toys to act out characters in a story were able to recall more information than those who only listened [Biazak]. However, another reading intervention using PMs was no better than a reading programme without PMs for enhancing children's receptive vocabulary, expressive vocabulary, or self-regulation [Dickinson]. Children who engaged in a guided play reading intervention with PMs, enacting fantasy or realistic stories, demonstrated gains in expressive and receptive vocabulary (with no difference between the two groups); however, it remains unclear if benefits were due to guided play or PMs as there were no other comparison conditions [Weisberg].

In the remaining two studies, literacy interventions involving PMs were compared to business-as-usual control groups with relatively older children (aged 6–9 years). One found that children in a literacy tutoring programme outperformed passive controls on a measure of phonological awareness, however pairwise comparisons between the intervention groups themselves were not reported (e.g., the same tutoring programme with vs. without PMs) [Lane]. The other study found that first (but not second or third) graders' reading scores improved more than controls following a comprehension strategy intervention with PMs [Cobb]. As these studies employed passive control groups, findings could be influenced by extraneous factors such as expectancy effects.

### Summary

Research on the use of PMs in literacy and reading interventions produced mixed results, with some finding improvements in children's vocabulary, literacy skills and memory for story content, while others reported null effects. Additionally, diversity in the methods used across these studies make it difficult to determine the specific impact of certain intervention features on the effectiveness of interventions. Even so, most of the studies used guided play, suggesting that PMs may be well suited for playful literacy approaches.

## Science-based interventions ($N = 9$)

### Intervention characteristics

#### *Materials and activities*

Children engaged in hands-on experimentation with a variety of objects and materials in the science-based interventions, exploring numerous concepts such as speed and slope, gravity, balance beam and mass, natural science (dinosaurs and fossils), simple machines (engineering and physics principles), buoyancy and magnetism. The level of playfulness and physical manipulation varied across these interventions: some interventions encouraged children to freely experiment with materials or develop their own solutions to engineering challenges, with adult guidance, while other activities were more structured, utilising specific materials and prescribed actions. See Table 5 for a summary of the science intervention study characteristics.

**TABLE 5** Characteristics of intervention studies involving science-based PMs ($n=9$).

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bulunuz 2013 | Turkey | 26 | 4–6 | QE, pre-post | School/ classroom | Class/ group | Teacher | >20 | Science-based (e.g., magnets, toy parachute, water/ice) | Curriculum approach to learn science concepts like gravity; playful experiments (e.g., mixing colours, using magnets; some not *hands*-on, e.g., watching seeds grow); adult support (questions, modelling) | Didactic approach (without hands-on activities) | Science-based |
| Dejonckh-eere 2016 | Belgium | 57 | 4–6 | RCT, pre-post | School/ classroom | Class/ group | Teacher | Unclear[1] | Science-based (e.g., magnets, objects that float or sink) | Exploratory play with science-based materials (e.g., magnets, objects that float or sink, balance scale) and adult guidance | Business-as-usual | Play-based |
| Lazonder 2014 | Netherlands | 60 | 10–12 | RCT, pre-post | Unclear | Individual | Researcher | 1 | Light & heavy tennis, soccer, & ping-pong balls | Children dropped different balls from 1 or 2 m & made predictions about which would hit the ground first | 1. Computerised drop task 2. Adult dropped (child observed) | Science-based |
| Li 2016 | China | 30 | 10–12 | RCT, pre-post | School/ classroom | Group | Teacher | 2–5 | LEGO engineering materials | Children collaborated to design & make ‘simple machines’ (e.g., crane, fan); teachers guided a design process: identify problem, develop solution, build & test | Same as intervention without the design process | Science-based |
| Lu 2018 | Taiwan | 53 | 10–12 | QE, pre-post | School/ classroom | Group | Unclear | 1 | Card puzzle | Children matched hexagonal dinosaur pieces with associated triangular pieces (fossils & dinosaur names) | Physical puzzle & virtual guidance (multimedia) | Science-based |

**TABLE 5** (Continued)

| ID | Location | Sample *N* | Age | Research design | Setting | Model of delivery | Adult involved | *N* sessions | Materials | Intervention | Comparison(s) | Main outcome domains |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Marulcu 2016 | USA | 31 | 10–12 | QE, pre-post | School/ classroom | Class/ pairs | Teacher | 11–12 | LEGO engineering materials | Children collaborated to plan & make a 'simple machine' ('people mover') using a design process: identify problem, develop & choose solution, build & test | Hands-on inquiry-based learning about levers & pulleys | Science-based |
| Portsmore 2010 | USA | 24 | 7–9 | QE, pre-post | School/ classroom | Class | Researcher | >20 | LEGO engineering materials | LEGO-engineering curriculum & story (Goldilocks): plan/ draw/built a solution to a design challenge; supported by teacher | Spontaneous LEGO-engineering (no planning stage) | Science-based |
| van Schijndel 2010 | Netherlands | 28 | 0–3 | QE, pre-post | Childcare centre | Group | Teacher | 6–10[2] | Sandpit & objects (e.g., ball, bucket, sieve, tubes) | Guided play in sandpit: slope/speed, & sorting/sets activities; exploration & experimentation encouraged by teacher (questions, modelling) | Free play in sandpit with same materials | Play-based |
| Zacharia 2012 | Cyprus | 80 | 4–6 | QE, pre-post | School/ classroom | Individual | Researcher | 1 | Balance beam & objects (e.g., toys, cubes) | Children could touch/hold objects to estimate their mass or place them on a balance beam to see if they balanced | Computerised objects & balance beam | Science-based |

*Note*: For inclusion in the review, a threshold of ≤20 was used for the child sample *N* (based on *N* included in analyses). The mean age of the sample was coded according to four categories (0–3, 4–6, 7–9, 10–12; i.e., it does not represent the age range). *N* sessions was also coded according to five categories (1, 2–5, 6–10, 11–20, >20). 'During-only' refers to outcome data being collected *during* the intervention activities only (i.e., findings not based on pre- or post-data). [1]Intervention took place over 7 weeks. [2]Programme lasted 6 weeks during regular playtime; children encouraged to participate at least once a week but could join whenever they liked.

Abbreviations: EIVP, explicit instruction vocabulary protocol; QE, quasi-experimental; RCT, randomised controlled trial.

*Physical engagement*

The degree of physical engagement varied among science-based interventions, with most having high demands. Children used complex LEGO engineering materials to design and construct *simple machines* such as levers or pulleys [Li; Marulcu; Portsmore], played in a sandpit and interacted with slope- and speed-related items such as tubes and small objects [van Schijndel], or actively engaged in hands-on experimentation to learn about various scientific concepts (e.g., determining if objects float or sink, playing with magnets, dropping items and observing the effects of gravity) [Bulunuz; Dejonckheere]. In contrast, other studies required lower levels of physical manipulation: children dropped balls from different heights (to learn about how factors like mass, size and height affect the fall of objects) [Lazonder], held and placed objects on balance beams [Zacharia], or matched triangle pieces (printed with fossils and dinosaur names) with corresponding hexagons [Lu]. In these three studies, PMs were compared to computer-based versions of the same tasks (e.g., a real vs. virtual balance beam).

*Type of instruction*

Three interventions were play-based, engaging children in hands-on activities that allowed for freedom and exploration, while also providing guidance and scaffolding from a teacher [Bulunuz; Dejonckheere; van Schijndel]. In one, children could freely explore and experiment with materials at different learning stations, each focused on a different science concept (e.g., magnets, gravity, water). They could also participate in problem-solving activities led by a teacher (e.g., removing paperclips from a glass of water using a magnet; [Bulunuz]). In the second study, children engaged in guided play in a sandpit, learning about slope and speed using objects such as plastic tubes and small items [van Schijndel]. In the third study, teachers provided science-based materials and demonstrated their use (e.g., magnets, objects that float or sink), then scaffolded children's exploratory play with the materials [Dejonckheere].

Studies involving LEGO engineering materials (i.e., making *simple* and/or *complex machines*) were not explicitly described as play-based, but included elements of guided play. Children were given a challenge, collaborated with peers, and were guided by an adult [Li; Marulcu; Portsmore]. The remaining three studies involved a game with rules [Lu] or a didactic approach that limited children's agency [Lazonder; Zacharia].

*Theoretical perspectives*

Theoretical foundations for the use of PMs in early science education were based on constructionism (Papert, 1980), which suggests children gain a deeper understanding through *learning by making* [Li], Sternberg's triarchic theory intelligence, which suggests that learning is attained through a combination of analytical, creative and practical abilities (Sternberg, 1895), and the concrete-to-abstract approach [Bulunuz; Lazonder; Zacharia].

## Evidence relating to effectiveness

Positive effects were reported following didactic interventions where children learned specific knowledge through a structured activity. One study found that 10-year-old children who engaged in a physical dropping task were more likely to revise their misconceptions about mass than those who engaged in a virtual dropping task or observed an adult [Lazonder]. Another study evaluated 5-year-olds' understanding of balance beams before and after participating in a physical or computerised balance beam task [Zacharia]. Children who initially had relatively lower levels of accurate prior knowledge about balance beams improved more in the physical versus virtual condition. In contrast, children (aged 10–11 years) learned more dinosaur-related knowledge by playing a virtual (augmented reality) game than a physical paper-based version [Lu]. However, these studies are limited: children only engaged in a single intervention session, tasks were highly constrained, and the generalisation of effects beyond specific target knowledge was not examined.

Positive effects were also reported in playful, curriculum-based studies involving hands-on experimentation [Bulunuz; van Schijndel]. Children (aged 5–6 years) in a guided play curriculum involving science-based learning stations performed better on an interview measure of science knowledge, compared to those taught using a didactic approach [Bulunuz]. However, the generalisation of children's learning to novel scenarios was not tested, meaning gains may not reflect improvements in conceptual understanding. In another study, young children (aged 2–3 years) engaged in more exploratory play following a guided play sandpit intervention than free play controls [van Schijndel]. Both studies were limited by small sample sizes (both had fewer than 30 participants).

Three studies found mixed effects of LEGO-based interventions using engineering materials with children ranging from 6 to 11 years old. In one study, the intervention enhanced children's knowledge of levers and pulleys more than an alternative (non-LEGO, but still hands-on) inquiry-based approach [Marulcu], and in the other two, children's physics knowledge and problem-solving abilities improved, but a design planning stage did not yield any added benefits [Li; Portsmore]. However, studies had small sample sizes (all had fewer than 32 participants) and lacked comparison conditions without PMs, making it difficult to determine the importance of physicality for learning.

## Summary

For pre-primary children, science education was facilitated through hands-on play-based learning, harnessing their natural curiosity to explore the world [Bulunuz; van Schijndel]. For older primary-age children, LEGO-based *simple machine* activities exposed them to engineering principles [Li; Marulcu; Portsmore]. Overall, there is evidence that pre-school-age and primary-school-age children can successfully learn scientific concepts through playful, creative, collaborative and active learning methods.

## Other learning outcomes ($N = 13$)

Three studies evaluated the *Six Bricks* guided play intervention, where each child received a set of six DUPLO bricks. In Kenya and South Africa, two studies trained teachers to incorporate PMs into their daily lessons using suggested activities. Visual perception, but not non-verbal reasoning, scores of children (aged 5–9) participating in *Six Bricks* improved more than those of passive controls [Brey; Jemutai]. However, the statistical models used were unclear [Brey] or positive effects were seen only with adjusted alphas ($p < 0.10$ but not $p < 0.05$). Another study of *Six Bricks* in Taiwan sought to promote positive emotions in children aged 10–11 years through collaborative building exercises but provided limited details about how the programme was delivered and the reported results were unclear [Harn] (see Appendix S1 for more details).

Five studies examined the effects of structured block play and reported benefits to infant's (aged 8 months) visual form sensitivity and young children's (aged 4–5 years) drawing skills [Sawyer; Schröder], but not numerosity discrimination, attention, inhibition, language acquisition, or social-emotional outcomes such as theory of mind and social interaction [Bugos, Christakis; Goldstein; Sawyer, Schröder]. Although one study found improvements in the language skills of a subset of children (aged 1–2 years) from low- and middle-income families [Christakis].

Two studies found that map-based puzzle activities did not enhance children's (aged 4–5 and 8–10 years) ability to retain geographic information compared to a non-puzzle map or virtual activity [Dang; Eisen]. An origami-based curriculum did not benefit 9-year-olds' social-emotional competencies compared to a social-emotional training programme [Raimundo]. Teaching infants (aged 8 months) specific actions to explore toys did not increase their exploratory behaviours [Clearfield], and toy play did not improve focused attention, comprehension or expressive vocabulary in 1-year-olds when compared with a book sharing intervention [Cooper].

### Boardgames and card games ($N=25$)

Twenty-five studies involved board and card games, which mostly ($n=20$) focused on children's numeracy skills. Most assessed the impact of linear number line [Bengtson; Bofferding; Cheung; Dunbar; Elofssen; Hawes; Ramani 2022, 2012a, 2012b; Siegler; Whyte] or grid-based boardgames [Chituk; Laski; Sonnenschein], usually targeting children's counting skills. Several studies compared linear number boardgames to circular number [e.g., Elofssen; Siegler; Ramani 2011] or linear colour boardgames [e.g., Hawes; Whyte; Dunbar; Ramani 2012a, 2012b]. Other maths interventions involved magnitude comparison card games [Ramani 2020; Scalise] or multiple games (e.g., Shut the Box, Lining-up the Fives) [Vogt]. In other domains, games focused on children's geography learning [Vargianniti] or cognitive and executive functioning [Estrada-Plana; Benzing; Türkoğlu]. Three studies compared physical and computerised games [Chituk; Drury; Fokides; Nikiforidou]. These studies are not discussed in further detail due to the limited degree of physical manipulation in the tasks and a summary table can be found in Appendix S1.

## DISCUSSION

This scoping review sought to identify and map studies evaluating PM interventions with pre-primary and primary-age children, an important step in identifying areas for future research. In total, 102 studies were included and broadly grouped into key learning domains and materials. This review is distinct from prior reviews as it established the breadth of PM literature regardless of intervention features such as learning domain, PM types or type of instruction. Considerable heterogeneity was found among these features.

Many of the reviewed studies focused on maths and numeracy interventions that utilised hands-on PM activities to promote children's overall maths skills or understanding of specific concepts such as fractions, geometry and counting. The abundance of maths-focused PM interventions is likely due to PMs being commonly used during regular maths lessons. This finding aligns with prior literature, where most reviews and meta-analyses of PM interventions are centred on maths learning (Carbonneau et al., 2013; Holmes, 2013; Lafay et al., 2019; Moyer-Packenham et al., 2013; Sarama & Clements, 2009; Tran et al., 2017). PM interventions promoting learning in other domains, including reading, literacy and science, were also found, but fewer studies were available in these areas.

There was substantial heterogeneity in the review studies regarding the intervention methods and approaches, echoing findings of previous literature reviews (Carbonneau et al., 2013; Lafay et al., 2019). Similarities and differences in intervention characteristics emerged across studies, including the instructional approach (e.g., play-based or formal instruction), PM materials (e.g., blocks, shapes, figurines) and activities (e.g., building, sorting, story enactment). Children's physical engagement with PMs also varied greatly. For example, simple counting tasks only required children to handle, touch or move small objects (Horan & Carr, 2018; Martin et al., 2012), whereas construction activities with blocks required higher levels of physical (and visual) manipulation for accurate block placement (Newman et al., 2016; Pirrone et al., 2018).

The overall findings regarding the effectiveness of PM interventions were mixed and often confounded by inconsistent and inadequate methodologies. In all the learning domains—maths/numeracy, reading/literacy and science—there was no consistent evidence that PM-based interventions improved children's learning. Nevertheless, there are positive results to note.

Reports indicated that maths-based interventions improved children's maths outcomes, consistent with prior reviews and meta-analytic data (Carbonneau et al., 2013; Holmes, 2013; Lafay et al., 2019). Studies showed that block-building interventions enhanced children's spatial talk, spatial reasoning and maths outcomes, consistent with previous research linking early block play, spatial skills and maths (Bower et al., 2020; Mix et al., 2016; Mix & Cheng, 2012; Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2014; Verdine, Golinkoff, Hirsh-Pasek, Newcombe, Filipowicz, et al., 2014). In other learning domains, selective benefits were seen in children's language and literacy skills following reading- and literacy-based interventions involving PMs, and in learning of scientific concepts and knowledge through hands-on activities and experimentation with science-focused materials. However, positive results were often outweighed by reports of null, negative or inconclusive findings. Prior systematic reviews confirm the educational benefits of PMs for maths learning, but the overall efficacy of PM interventions in other learning domains has not been thoroughly evaluated in early childhood. Systematic reviews and meta-analyses of reading, literacy and science-based PM interventions are recommended.

Promising results were found in playful, curriculum-based interventions where children participated in extensive programmes (>20 sessions with multiple activities) using maths- or science-based PMs (Bulunuz, 2013; Cramer et al., 2002; Dennis, 2012; Hull et al., 2018; Sophian, 2004; Starkey et al., 2004; van Schijndel et al., 2010). For instance, one study implemented a multifaceted intervention to meet the needs of primary education in Belize, focusing on teacher knowledge and school resources (Hull et al., 2018). A large-scale effectiveness trial found larger improvements in the maths achievement scores of intervention children versus controls, leading to a nationwide rollout of the intervention. The study demonstrates best practices for producing stronger and reliable data, in terms of intervention development (e.g., meeting the needs of the educational context, grounded in evidence) and trial design (e.g., robust methods and analyses). Both contribute to the success of an intervention and its potential real-world impact on policy and practice. Another study with strong methods, in the USA, showed that preschool children benefited from a playful, curriculum-based intervention that comprised a range of hands-on maths activities and ongoing support for teachers (Sophian, 2004).

Overall, the field lacks high-quality research with robust research designs. Many studies had methodological limitations such as small sample sizes, lack of control (or active control) groups, missing baseline data, inadequate outcome/transfer measures (e.g., researcher-made or closely tied to intervention tasks) and/or inadequate statistical analyses or reporting of analyses. Prior reviews have also shown substantial variation and flaws in the methodologies of PM interventions (Carbonneau et al., 2013; Lafay et al., 2019). Future evaluations of PM interventions should be methodologically strong to ensure that data related to effectiveness is reliable and robust, thus giving interventions that are deemed effective the best chance of being scaled and impacting policy.

Reasons for incorporating hands-on activities to promote learning in the review studies were consistent with wider literature. Many papers cited the concrete-to-abstract approach, which is based on early developmental theories (Bruner, 1964; Piaget, 1962), and suggests that children learn abstract, symbolic concepts more effectively with physical referents. In maths, children can understand fractions by placing five 1/5th fraction tiles together and observing that they equal one larger fraction tile representing one whole. Manipulating objects can also help children to make connections between the physical world and words by facilitating indexing, the process of acquiring semantic information about new words (e.g., playing with toy tractors and horses when reading a story about a farm) (Glenberg, 2008; Glenberg et al., 2004). Zacharia et al. (2012) also stress the importance of hands-on experiences with science materials and apparatus (Zacharia et al., 2012), which provide children with opportunities to engage in fundamental aspects of scientific discovery, such as forming hypotheses, conducting experiments and evaluating evidence (Zimmerman, 2007). Although scientific reasoning skills develop throughout preschool and primary school years (Piekny et al., 2014; Sodian et al., 1991), research on hands-on science interventions in this age group is lacking, highlighting the need for age-appropriate science programmes in preschool and primary education.

There was no convincing evidence that PMs were better than virtual materials for enhancing children's maths learning; most studies reported that PMs were no better or worse than virtual materials (Mendiburo & Hasselbring, 2011; Moyer-Packenham & Westenskow, 2013). Although the educational benefits of PMs during maths instruction are well established (Carbonneau et al., 2013; Holmes, 2013; Lafay et al., 2019), the physical nature of the materials used in these interventions may not be critical. In contrast, there was positive, yet limited, evidence that children learn some science concepts more effectively with physical than virtual materials (Lazonder & Ehrenhard, 2014; Zacharia et al., 2012).

Instructional guidance varied across interventions, with most using either a guided play or didactic approach. Some experimental studies manipulated the degree of adult guidance and child agency between intervention conditions. Most studies reported that guided play with PMs was more beneficial for children's visual-spatial, language, and exploratory play outcomes than free play with the same or similar materials. This is consistent with recent meta-analytic data showing that guided play interventions improve children's early maths skills and spatial talk more than free play (Skene et al., 2022).

PMs facilitate activities that promote children's active participation in learning and are common in play-based pedagogy (Pyle et al., 2017; Skene et al., 2022). Playful activities with PMs may have an indirect effect on learning by promoting children's attitudes to learning, such as enjoyment and intrinsic motivation. Due to the broad range of interventions captured in this review, the specific effects of guided play with PMs cannot be disentangled from other variables (e.g., differences in the types of materials and/or the amount of physical engagement with PMs). Although Skene et al. (2022) investigated the effectiveness of guided play interventions (regardless of PMs) compared to other types of instruction, and examined potential moderators via subgroup analyses, the type of intervention materials or presence of PMs was not considered. Further systematic investigation may help to disentangle the relative impact of PMs and guidance.

Studies were overwhelmingly conducted in high-income countries, with over half taking place in the USA, thus limiting the generalisability of study findings and the potential transferability of interventions to novel contexts and educational systems. There is pressing need for more research in middle- and low-income countries. Recommendations include: (a) implement and scale interventions with pre-existing evidence or design interventions with evidence-based components; (b) pilot before implementation and scaling if evidence is mainly derived from high-income contexts; (c) design multifaceted interventions that meet context-specific needs (making adaptations to ensure programmes are useful, acceptable and feasible for the context)—considering factors like existing teacher training (or lack thereof), typical teaching practice, stakeholder expectations and cost; and (d) conduct methodologically robust studies that produce strong and reliable data to support scaling and policy impact. Several limitations of this scoping review are noted. The review synthesised many studies but did not include an in-depth examination of each paper, potentially leading to the omission of important information (e.g., related to individual differences or intervention fidelity). The review aimed to encompass a wide range of educational interventions using broad inclusion criteria, regardless of research design. Consequently, the review included both long-term educational programmes integrated into curriculums and short-term experimental interventions conducted under lab-like conditions, with additional differences in factors such as comparison groups, study design, materials and outcomes. This heterogeneity makes it difficult to directly compare studies and draw overall conclusions about the effectiveness of PM interventions.

The search terms used in this review did not encompass all the types of PMs that could be utilised in educational interventions, in part due to the limited use of the term *manipulative* outside of maths activities. A relatively small number of science-based studies were identified ($n=9$), despite the vast array of materials that could be used for hands-on science learning. Indeed, the studies included a diverse range of materials, such as magnets, parachutes, sand, tubes, water, ice, balance beams, and so on. More targeted searches using terms related to specific science-based materials and concepts may yield additional reports involving PMs for early scientific learning and experimentation. Similarly, a more targeted systematic search may also yield more literacy-based PM intervention studies not captured in this review.

This review focused on the conceptual aspects of interventions that related to children's experiences (instruction, agency, play, interaction with materials). Other important factors (e.g., study design, number of sessions, child age, adult involved) are summarised in tables but not examined closely. Further systematic reviews and meta-analyses could explore the impact on these study features on the effectiveness of PM interventions, and systematically examine research quality.

A major drawback of the review were resource constraints. Only one researcher conducted most of the review procedure, meaning that double screening and data extraction of all studies could not take place, limiting the reliability of the findings and increasing the likelihood of bias. There were also deviations from the protocol (e.g., no searches of the grey literature, except for dissertations/theses). Finally, only reports written in English were included.

Based on the information gathered in this review, several key recommendations for using PMs in practice are suggested: (a) choose materials and activities that are age-appropriate and focused on the learning goal; (b) consider the type and amount of instructional guidance needed (adjusted based on learning content and children's needs); and (c) consider the level of physical interaction afforded by materials and activities and its importance for the learning goal.

## CONCLUSION

A diverse range of PM interventions were captured in this scoping review, with substantial differences in intervention features such as the learning content, hands-on activities and materials, participant age, adult involved (and their training), mode of instruction, number of sessions, and study factors related to research design and quality (e.g., control groups, sample sizes, analyses). Although positive outcomes were reported in children's maths, spatial, literacy and science skills, evidence was inconsistent and many studies had methodological limitations, leading to the need for caution in drawing conclusions about the overall effectiveness of PM interventions. Most studies were conducted in high-income countries and focused on children's maths skills, highlighting the need for research expansion in other contexts and learning domains.

## FUNDING INFORMATION

The work presented in this article is supported by an unrestricted donation to the primary author's research centre from the LEGO Foundation.

## CONFLICT OF INTEREST STATEMENT

Dr Byrne and Prof Ramchandani were based in the Play in Education, Development, and Learning (PEDAL) Research Centre at the University of Cambridge when this research was conducted. PEDAL received a donation for funding from the LEGO Foundation. Dr Jensen and Dr Stjerne Thomsen are both employed by the LEGO Foundation.

## DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study. References for the included studies are provided in Appendix S1.

## ETHICS STATEMENT

The research did not access raw data. The scoping review aggregated studies that had already received ethical approval, consequently, no additional ethical approval was necessary.

## PREREGISTRATION

A protocol was registered with the Open Science Framework (OSF; https://osf.io/p4jk9/).

## REFERENCES

Alfieri, L., Brooks, P. J., Aldrich, N. J., & Tenenbaum, H. R. (2011). Does discovery-based instruction enhance learning? *Journal of Educational Psychology*, *103*(1), 1–18. https://doi.org/10.1037/a0021017

Arksey, H., & O'Malley, L. (2005). Scoping studies: Towards a methodological framework. *International Journal of Social Research Methodology: Theory and Practice*, *8*(1), 19–32. https://doi.org/10.1080/1364557032000119616

Barsalou, L. W. (2007). Grounded Cognition. *Annual Review of Psychology*, *59*, 617–645. https://doi.org/10.1146/Annurev.Psych.59.103006.093639

Battista, M. T. (1990). Spatial visualization and gender differences in high school geometry. *Journal for Research in Mathematics Education*, *21*(1), 47. https://doi.org/10.2307/749456

Botha, M., Maree, J. G., & de Witt, M. W. (2005). Developing and piloting the planning for facilitating mathematical processes and strategies for preschool learners. *Early Child Development and Care*, *175*(7–8), 697–717. https://doi.org/10.1080/0300443042000302582

Bouck, E. C., & Park, J. (2018). A systematic review of the literature on mathematics manipulatives to support students with disabilities. *Education and Treatment of Children*, *41*(1), 65–106. https://doi.org/10.4324/9780203416761_chapter_8

Bower, C., Odean, R., Verdine, B. N., Medford, J. R., Marzouk, M., Golinkoff, R. M., & Hirsh-Pasek, K. (2020). Associations of 3-year-olds' block-building complexity with later spatial and mathematical skills. *Journal of Cognition and Development*, *21*(3), 383–405. https://doi.org/10.1080/15248372.2020.1741363

Bruner, J. S. (1964). The course of cognitive growth. *American Psychologist*, *19*(1), 1–15. https://doi.org/10.1037/H0044160

Bulunuz, M. (2013). Teaching science through play in kindergarten: Does integrated play and science instruction build understanding? *European Early Childhood Education Research Journal*, *21*(2), 226–249. https://doi.org/10.1080/1350293X.2013.789195

Caglak, S. (2017). Does hands-on science practices make an impact on achievement in science? A meta-analysis. *Journal of Education in Science Environment and Health*, *3*(1), 69–87. https://doi.org/10.21891/jeseh.275708

Caldera, Y. M., Culp, A. M. D., O'Brien, M., Truglio, R. T., Alvarez, M., & Huston, A. C. (1999). Children's play preferences, construction play with blocks, and visual-spatial skills: Are they related? *International Journal of Behavioral Development*, *23*(4), 855–872. https://doi.org/10.1080/016502599383577

Carbonneau, K. J., Marley, S. C., & Selig, J. P. (2013). A meta-analysis of the efficacy of teaching mathematics with concrete manipulatives. *Journal of Educational Psychology*, *105*(2), 380–400. https://doi.org/10.1037/a0031084

Casey, B. M., Pezaris, E. E., & Bassi, J. (2012). Adolescent boys' and girls' block constructions differ in structural balance: A block-building characteristic related to math achievement. *Learning and Individual Differences*, *22*(1), 25–36. https://doi.org/10.1016/j.lindif.2011.11.008

Charlesworth, R., & Lind, K. K. (2003). *Math and science for young children* (4th ed.). Delmar Learning.
Clements, D. H., & Sarama, J. (2008). Experimental evaluation of the effects of a research-based preschool mathematics curriculum. *American Educational Research Journal*, *45*(2), 443–494. https://doi.org/10.3102/0002831207312908
Cramer, K. A., Post, T. R., & Delmas, R. C. (2002). Initial fraction learning by fourth- and fifth-grade students: A comparison of the effects of using commercial curricula with the effects of using the rational number project curriculum. *Journal for Research in Mathematics Education*, *33*(2), 111–144. https://doi.org/10.2307/749646
Dennis, C. (2012). *The effects of the use of manipulatives on the comprehension of math concepts among fifth grade students*. [*EBSCOhost*, Northcentral University]. https://web-b-ebscohost-com.ezp.lib.cam.ac.uk/ehost/detail/detail?vid=0&sid=8aa095fc-031b-4f94-ad96-2e30d73905d5%40pdc-v-sessmgr02&bdata=JnNpdGU9ZWhvc3QtbGl2ZSZzY29wZT1zaXRl#AN=2012-99190-512&db=psyh
Engelkamp, J., Zimmer, H. D., Mohr, G., & Sellen, O. (1994). Memory of self-performed tasks: Self-performing during recognition. *Memory & Cognition*, *22*(1), 34–39. https://doi.org/10.3758/BF03202759
Fernández-Méndez, L. M., Contreras, M. J., Mammarella, I. C., Feraco, T., & Meneghetti, C. (2020). Mathematical achievement: The role of spatial and motor skills in 6–8 year-old children. *PeerJ*, *8*, e10095. https://doi.org/10.7717/PEERJ.10095
Fisher, K., Hirsh-Pasek, K., Golinkoff, R. M., Singer, D. G., & Berk, L. (2012). *Playing around in school: Implications for learning and educational policy*. In *the Oxford Handbook of the Development of Play* https://doi.org/10.1093/oxfordhb/9780195393002.013.0025
Glenberg, A. M. (2008). Embodiment for education. In *Handbook of cognitive science* (pp. 355–372). Elsevier Ltd. https://doi.org/10.1016/B978-0-08-046616-3.00018-9
Glenberg, A. M., Gutierrez, T., Levin, J. R., Japuntich, S., & Kaschak, M. P. (2004). Activity and imagined activity can enhance young children's reading comprehension. *Journal of Educational Psychology*, *96*(3), 424–436. https://doi.org/10.1037/0022-0663.96.3.424
Grossman, J., & Mackenzie, F. J. (2005). The randomized controlled trial: Gold standard, or merely standard? *Perspectives in Biology and Medicine*, *48*(4), 516–534. https://doi.org/10.1353/PBM.2005.0092
Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). The relation between spatial skill and early number knowledge: The role of the linear number line. *Developmental psychology*, *48*(5), 1229. https://doi.org/10.1037/a0027433
Hariton, E., & Locascio, J. J. (2018). Randomised controlled trials—The gold standard for effectiveness research. *BJOG: An International Journal of Obstetrics and Gynaecology*, *125*(13), 1716. https://doi.org/10.1111/1471-0528.15199
Hirsh-Pasek, K., Michnick Golinkoff, R., Berk, L. E., & Singer, D. (2010). *A mandate for playful learning in preschool: Presenting the evidence*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195382716.001.0001
Holmes, A. B. (2013). *Effects of manipulative use on PK-12 mathematics achievement: A meta-analysis*. Society for Research on Educational Effectiveness.
Horan, E., & Carr, M. (2018). How much guidance do students need? An intervention study on kindergarten mathematics with manipulatives. *International Journal of Educational Psychology*, *7*(3), 286–316. https://doi.org/10.17583/ijep.2018.3672
Hull, D. M., Hinerman, K. M., Ferguson, S. L., Chen, Q., & Näslund-Hadley, E. I. (2018). Teacher-led math inquiry: A cluster randomized trial in Belize. *Educational Evaluation and Policy Analysis*, *40*(3), 336–358. https://doi.org/10.3102/0162373718768430
Jirout, J. J., & Newcombe, N. S. (2015). Building blocks for developing spatial skills: Evidence from a large, representative U.S. Sample. *Psychological Science*, *26*(3), 302–310. https://doi.org/10.1177/0956797614563338
Khine, M. S. (2016). *Visual-spatial ability in STEM education: Transforming research into practice*. Springer International Publishing. https://doi.org/10.1007/978-3-319-44385-0
Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, *41*(2), 75–86. https://doi.org/10.1207/s15326985ep4102_1
Kyttälä, M., Aunio, P., Lehto, J. E., van Luit, J., & Hautamäki, J. (2003). Visuospatial working memory and early numeracy. *Educational and Child Psychology*, *20*, 65–76.
Kyttälä, M., & Lehto, J. E. (2008). Some factors underlying mathematical performance: The role of visuospatial working memory and non-verbal intelligence. *European Journal of Psychology of Education*, *23*(1), 77–94. https://doi.org/10.1007/BF03173141
Lafay, A., Osana, H. P., & Valat, M. (2019). Effects of interventions with manipulatives on immediate learning, maintenance, and transfer in children with mathematics learning disabilities: A systematic review. *Education Research International*, *2019*, 1–21. https://doi.org/10.1155/2019/2142948

Lazonder, A. W., & Ehrenhard, S. (2014). Relative effectiveness of physical and virtual manipulatives for conceptual change in science: How falling objects fall. *Journal of Computer Assisted Learning*, *30*(2), 110–120. https://doi.org/10.1111/jcal.12024
Levac, D., Colquhoun, H., & Brien, K. K. O. (2010). *Scoping studies: Advancing the methodology. Implemenatation Science*, *5*, 1–9.
Levine, S. C., Ratliff, K. R., Huttenlocher, J., & Cannon, J. (2012). Early puzzle play: A predictor of preschoolers' spatial transformation skill. *Developmental Psychology*, *48*(2), 530–542. https://doi.org/10.1037/a0025913
Lilienfeld, S. O., McKay, D., & Hollon, S. D. (2018). Why randomised controlled trials of psychological treatments are still essential. *The Lancet Psychiatry*, *5*(7), 536–538. https://doi.org/10.1016/S2215-0366(18)30045-2
Marley, S. C., & Carbonneau, K. J. (2014). Theoretical perspectives and empirical evidence relevant to classroom instruction with manipulatives. *Educational Psychology Review*, *26*(1), 1–7. https://doi.org/10.1007/S10648-014-9257-3
Martin, T., Svihla, V., & Smith, C. P. (2012). The role of physical action in fraction learning. *Journal of Education and Human Development*, *5*(1), 1–17.
Mendiburo, M., & Hasselbring, T. (2011). *Technology's Impact on Fraction Learning: An experimental comparison of virtual and physical manipulatives, presented at the Society for Research on Education Effectiveness (SREE) Conference, Tennessee, USA, 2011*.
Mix, K. S., & Cheng, Y. L. (2012). The relation between space and math. Developmental and educational implications. In *Advances in child development and behavior* (Vol. *42*, pp. 197–243). Academic Press Inc. https://doi.org/10.1016/B978-0-12-394388-0.00006-X
Mix, K. S., Levine, S. C., Cheng, Y. L., Young, C., Hambrick, D. Z., Ping, R., & Konstantopoulos, S. (2016). Separate but correlated: The latent structure of space and mathematics across development. *Journal of Experimental Psychology: General*, *145*(9), 1206–1227. https://doi.org/10.1037/xge0000182
Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Altman, D., Antes, G., Atkins, D., Barbour, V., Barrowman, N., Berlin, J. A., Clark, J., Clarke, M., Cook, D., D'Amico, R., Deeks, J. J., Devereaux, P. J., Dickersin, K., Egger, M., Ernst, E., … Tugwell, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Annals of Internal Medicine*, *151*(4), 264–269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135
Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., & Stewart, L. A. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic Reviews*, *4*(1), 1. https://doi.org/10.1186/2046-4053-4-1
Möhring, W., & Frick, A. (2013). Touching up mental rotation: Effects of manual experience on 6-month-old infants' mental object rotation. *Child Development*, *84*(5), 1554–1565. https://doi.org/10.1111/cdev.12065
Montessori, M. (1964). *The Montessori method*. Schocken Books.
Morris, B. J., Croker, S., Masnick, A. M., Zimmerman, C., Morris, B. J., Croker, S., Masnick, A. M., & Zimmerman, C. (2012). The emergence of scientific reasoning. In *Current Topics in Children's Learning and Cognition*. IntechOpen. https://doi.org/10.5772/53885
Moyer-Packenham, P. S., Baker, J., Westenskow, A., Anderson, K., Shumway, J., Rodzon, K., & Jordan, K. (2013). A study comparing virtual manipulatives with other instructional treatments in third- and fourth-grade classrooms. *Journal of Education*, *193*(2), 25–39. https://doi.org/10.1177/002205741319300204
Moyer-Packenham, P. S., & Westenskow, A. (2013). Effects of virtual manipulatives on student achievement and mathematics learning. *International Journal of Virtual and Personal Learning Environments*, *4*(3), 35–50. https://doi.org/10.4018/jvple.2013070103
Mulligan, N. W., & Hornstein, S. L. (2003). Memory for actions: Self-performed tasks and the reenactment effect. *Memory and Cognition*, *31*(3), 412–421. https://doi.org/10.3758/BF03194399
Newman, S. D., Hansen, M. T., & Gutierrez, A. (2016). An fMRI study of the impact of block building and board games on spatial ability. *Frontiers in Psychology*, *7*, 1278. https://doi.org/10.3389/fpsyg.2016.01278
Pellegrini, A. D., & Gustafson, K. (2005). Boys' and Girls' uses of objects for exploration, play, and tools in early childhood. In A. D. Pellegrini & P. K. Smith (Eds.), *The nature of play: Great apes and humans* (pp. 113–135). Guilford Press. https://doi.org/10.4324/9781351216869-7
Peters, M. D. J., Godfrey, C. M., Khalil, H., McInerney, P., Parker, D., & Soares, C. B. (2015). Guidance for conducting systematic scoping reviews. *International Journal of Evidence-Based Healthcare*, *13*(3), 141–146. https://doi.org/10.1097/XEB.0000000000000050
Piaget, J. (1952). *The origins of intelligence in children* (p. 419). W W Norton & Co. https://doi.org/10.1037/11494-000
Piaget, J. (1962). *Play, dreams and imitation in children*. WW Norton & Co.
Piaget, J., & Inhelder, B. (2014). Intellectual operations and their development. In *Experimental Psychology its Scope and Method: VII Intelligence* (pp. 144–205). Psychology Press. https://doi.org/10.4324/9781315756547-8
Piekny, J., Grube, D., & Maehler, C. (2014). The development of experimentation and evidence evaluation skills at preschool age. *International Journal of Science Education*, *36*(2), 334–354. https://doi.org/10.1080/09500693.2013.776192

Pirrone, C., Tienken, C. H., Pagano, T., & di Nuovo, S. (2018). The influence of building block play on mathematics achievement and logical and divergent thinking in Italian primary school mathematics classes. *The Educational Forum*, *82*(1), 40–58. https://doi.org/10.1080/00131725.2018.1379581

Pound, L. (2006). *Supporting mathematical development in early years*. O. U. Press.

Pyle, A., & Danniels, E. (2017). A continuum of play-based learning: The role of the teacher in play-based pedagogy and the fear of hijacking play. *Early Education and Development*, *28*(3), 274–289. https://doi.org/10.1080/10409289.2016.1220771

Pyle, A., DeLuca, C., & Danniels, E. (2017). A scoping review of research on play-based pedagogies in kindergarten education. *Review of Education*, *5*(3), 311–351. https://doi.org/10.1002/rev3.3097

Rittle-Johnson, B., & Koedinger, K. R. (2005). Designing knowledge scaffolds to support mathematical problem solving. *Cognition and Instruction*, *23*(3), 313–349. https://doi.org/10.1207/s1532690xci2303_1

Sarama, J., & Clements, D. H. (2009). 'Concrete' computer manipulatives in mathematics education. *Child Development Perspectives*, *3*(3), 145–150. https://doi.org/10.1111/j.1750-8606.2009.00095.x

Schwichow, M., Zimmerman, C., Croker, S., & Härtig, H. (2016). What students learn from hands-on activities. *Journal of Research in Science Teaching*, *53*(7), 980–1002. https://doi.org/10.1002/tea.21320

Skene, K., O'Farrelly, C. M., Byrne, E. M., Kirby, N., Stevens, E. C., & Ramchandani, P. G. (2022). Can guidance during play enhance children's learning and development in educational contexts? A systematic review and meta-analysis. *Child Development*, *93*(4), 1162–1180. https://doi.org/10.1111/cdev.13730

Sodian, B., Zaitchik, D., & Carey, S. (1991). Young children's differentiation of hypothetical beliefs from evidence. *Child Development*, *62*, 753–766. https://doi.org/10.2307/1131175

Sophian, C. (2004). Mathematics for the future: Developing a head start curriculum to support mathematics learning. *Early Childhood Research Quarterly*, *19*(1), 59–81.

Starkey, P., Klein, A., & Wakeley, A. (2004). Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention. *Early Childhood Research Quarterly*, *19*(1), 99–120. https://doi.org/10.1016/j.ecresq.2004.01.002

Taylor, M. E., & Boyer, W. (2020). Play-based learning: Evidence-based research to improve Children's learning experiences in the kindergarten classroom. *Early Childhood Education Journal*, *48*(2), 127–133. https://doi.org/10.1007/s10643-019-00989-7

Thomas, J., Brunton, J., & Graziosi, S. (2010). *EPPI-Reviewer 4.0: Software for research synthesis*. EPPI-Centre Software. London: Social Science Research Unit, Institute of Education, University of London.

Thompson, J. M., Nuerk, H. C., Moeller, K., & Cohen Kadosh, R. (2013). The link between mental rotation ability and basic numerical representations. *Acta Psychologica*, *144*, 324–331. https://doi.org/10.1016/j.actpsy.2013.05.009

Thompson, T. (2016). *The effects of concrete, virtual, and multimodal tangram manipulatives on second grade elementary students' mathematics achievement and development of spatial sense: A convergent parallel mixed methods study*. Oklahoma State University.

Tolar, T. D., Lederberg, A. R., & Fletcher, J. M. (2009). A structural model of algebra achievement: Computational fluency and spatial visualisation as mediators of the effect of working memory on algebra achievement. *Educational Psychology*, *29*(2), 239–266. https://doi.org/10.1080/01443410802708903

Toub, T. S., Hassinger-Das, B., Nesbitt, K. T., Ilgaz, H., Weisberg, D. S., Hirsh-Pasek, K., Golinkoff, R. M., Nicolopoulou, A., & Dickinson, D. K. (2018). The language of play: Developing preschool vocabulary through play following shared book-reading. *Early Childhood Research Quarterly*, *45*, 1–17. https://doi.org/10.1016/j.ecresq.2018.01.010

Tran, C., Smith, B., & Buschkuehl, M. (2017). Support of mathematical thinking through embodied cognition: Nondigital and digital approaches. *Cognitive Research: Principles and Implications*, *2*(1), 16. https://doi.org/10.1186/s41235-017-0053-8

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H. L., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., … Straus, S. E. (2018). PRISMA extension for scoping reviews (PRISMA-ScR): Checklist and explanation. *Annals of Internal Medicine*, *169*(7), 467–473. https://doi.org/10.7326/M18-0850

Trivette, C. M., Simkus, A., Dunst, C. J., & Hamby, D. W. (2012). Repeated book Reading and Preschoolers' early literacy development. *Centre for Early Literacy Learning*, *5*(5), 1–13.

van Schijndel, T. J. P., Singer, E., van der Maas, H. L. J., & Raijmakers, M. E. J. (2010). A sciencing programme and young children's exploratory play in the sandpit. *European Journal of Developmental Psychology*, *7*(5), 603–617. https://doi.org/10.1080/17405620903412344

Vander Heyden, K. M., Huizinga, M., & Jolles, J. (2017). Effects of a classroom intervention with spatial play materials on children's object and viewer transformation abilities. *Developmental Psychology*, *53*(2), 290–305. https://doi.org/10.1037/dev0000224

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2014). Finding the missing piece: Blocks, puzzles, and shapes fuel school readiness. *Trends in Neuroscience and Education*, *3*(1), 7–13. https://doi.org/10.1016/j.tine.2014.02.005

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., Newcombe, N. S., Filipowicz, A. T., & Chang, A. (2014). Deconstructing building blocks: Preschoolers' spatial assembly performance relates to early mathematical skills. *Child Development*, *85*(3), 1062–1076. https://doi.org/10.1111/cdev.12165

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*(4), 817–835. https://doi.org/10.1037/a0016127

Weisberg, D. S., Hirsh-Pasek, K., & Golinkoff, R. M. (2013). Embracing complexity: Rethinking the relation between play and learning: Comment on Lillard et al. *Psychological Bulletin*, *139*(1), 35–39. https://doi.org/10.1037/a0030077

Weisberg, D. S., Hirsh-Pasek, K., & Golinkoff, R. M. (2013). Guided play: Where curricular goals meet a playful pedagogy. *Mind, Brain, and Education*, *7*(2), 104–112. https://doi.org/10.1111/mbe.12015

Weisberg, D. S., Hirsh-Pasek, K., Golinkoff, R. M., Kittredge, A. K., & Klahr, D. (2016). Guided play: Principles and practices. *Current Directions in Psychological Science*, *25*(3), 177–182. https://doi.org/10.1177/0963721416645512

Whitebread, D. (2012). *Developmental psychology and early childhood education: A guide for students and practitioners*. SAGE Publications Ltd.

Whitebread, D. (2019). Overview: The contribution of research in Developmental Psychology to early childhood education. In D. Whitebread, V. Grau, K. Kumpulainen, M. M. McClelland, N. E. Perry, & D. Pino-Pasternak (Eds.), *The SAGE handbook of Developmental Psychology and early childhood education* (pp. 1–20). SAGE Publications Ltd. https://doi.org/10.4135/9781526470393

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*(4), 625–636. https://doi.org/10.3758/BF03196322

Wolfgang, C. H., Stannard, L. L., & Jones, I. (2001). Block play performance among preschoolers as a predictor of later school achievement in mathematics. *Journal of Research in Childhood Education*, *15*(2), 173–180. https://doi.org/10.1080/02568540109594958

Wolfgang, C. H., Stannard, L. L., & Jones, I. (2003). Advanced constructional play with legos among preschoolers as a predictor of later school achievement in mathematics. *Early Child Development and Care*, *173*(5), 467–475. https://doi.org/10.1080/0300443032000088212

World Bank. (2021). GNI per capita, atlas method (current US$) data. World Bank Group US. https://data.worldbank.org/indicator/NY.GNP.PCAP.CD

Yang, W., Liu, H., Chen, N., Xu, P., & Lin, X. (2020). Is early spatial skills training effective? A meta-analysis. *Frontiers in Psychology*, *11*, 1938. https://doi.org/10.3389/fpsyg.2020.01938

Yu, Y., Shafto, P., Bonawitz, E., Yang, S. C. H., Golinkoff, R. M., Corriveau, K. H., Hirsh-Pasek, K., & Xu, F. (2018). The theoretical and methodological opportunities afforded by guided play with young children. *Frontiers in Psychology*, *9*, 1152. https://doi.org/10.3389/fpsyg.2018.01152

Zacharia, Z. C., Loizou, E., & Papaevripidou, M. (2012). Is physicality an important aspect of learning through science experimentation among kindergarten students? *Early Childhood Research Quarterly*, *27*(3), 447–457. https://doi.org/10.1016/j.ecresq.2012.02.004

Zimmerman, C. (2007). The development of scientific thinking skills in elementary and middle school. *Developmental Review*, *27*(2), 172–223. https://doi.org/10.1016/j.dr.2006.12.001

Zosh, J. M., Hirsh-Pasek, K., Hopkins, E. J., Jensen, H., Liu, C., Neale, D., Solis, S. L., & Whitebread, D. (2018). Accessing the inaccessible: Redefining play as a spectrum. *Frontiers in Psychology*, *9*, 1124. https://doi.org/10.3389/fpsyg.2018.01124

Zosh, J. M., Hopkins, E. J., Jensen, H., Liu, C., Neale, D., Hirsh-Pasek, K., Solis, S. L., & Whitebread, D. (2017). *Learning through play: A review of the evidence (white paper)* (p. 40). The LEGO Foundation.

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Byrne, E. M., Jensen, H., Thomsen, B. S., & Ramchandani, P. G. (2023). Educational interventions involving physical manipulatives for improving children's learning and development: A scoping review. *Review of Education*, *11*, e3400. https://doi.org/10.1002/rev3.3400