Effectiveness of Educational Technology in Early Mathematics Education: A Systematic Literature Review

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Abstract

Despite the general agreement regarding the importance of stimulating young children's early mathematical skills, mathematical learning opportunities in preschool are limited. Educational technology (ET) may be an effective tool to address this problem. Taking into account the weaknesses of previous reviews, we conducted a systematic and comprehensive review of the research literature on the effectiveness of ET in early mathematics education, critically analyzing the findings of studies adhering to a media comparison approach (comparing an ET condition to a non-ET condition or another ET condition) versus studies following a value-added approach (comparing at least two ET conditions which only differ with respect to one feature in the ET or in its implementation). Reviewing 54 studies, we systematically analyzed (1) the effectiveness of ET, (2) the features of the ET and ET implementation associated with ET effectiveness, and (3) child characteristics associated with ET effectiveness. Our analyses indicated that media comparison studies comparing an ET to a non-ET condition provide evidence for the effectiveness of ET for enhancing young children's mathematical competencies. Second, value-added studies pointed to ET implementation features associated with ET effectiveness, namely teacher support during ET use and an individual grouping structure. Finally, both media comparison and value-added studies revealed that ET effectiveness is associated with children's performance in the ET and with their prior knowledge. To further advance the field, value-added studies on features of the ET and its implementation are required, as well as studies focusing on important child characteristics that are associated with ET effectiveness.

Keywords: early mathematics education; media comparison approach; value-added approach; educational technology; systematic literature review

1. Introduction

Young children's early mathematical skills are strong and stable predictors of their later mathematical achievement [1]. It is therefore crucial to equip young children with sound basic mathematical competencies by employing effective instructional interventions. Yet, international studies indicate that instruction in the domain of early mathematics in preschools is limited in terms of both frequency and content [2,3]. A potential pedagogical approach to support the development of early mathematical skills is educational technology (ET), which refers to "electronic tools and applications that help deliver learning content and support the learning process" [4]. A growing body of literature recognizes the potential of ET for improving learning outcomes in a variety of content domains, including the domain of mathematics. Several meta-analyses underscore the effectiveness of ET in primary and secondary mathematics education (e.g., [5,6,7]). Although research also provides increasing evidence that ET can be an effective tool for supporting early mathematical development [8], a recent and comprehensive systematic literature review synthesizing this growing body of evidence is currently lacking. Previous literature reviews on the topic suffer from several theoretical and methodological weaknesses as they are outdated, especially taking into account the evolutions in ET applications (i.e., [9,10]), focus on a specific subgroup of children (i.e., [11,12]), are not systematically conducted, and thus, not comprehensive (i.e., [9, 10,12,13]), and do not take into account differences in the study designs, especially with respect to the activities that were conducted in the control conditions [9,10,11,12,13,14]. We aimed to address these weaknesses by conducting a systematic and comprehensive literature review on the effectiveness of ET for stimulating children's development in the domain of early mathematics, with explicit attention for the insights coming from media comparison studies versus value-added studies in the domain. In doing so, we aimed to inform both research, on the gaps in the existing evidence and opportunities for future research, and educational practice, on effective tools for stimulating children's early mathematical development and effective approaches for designing and implementing these tools.

The following sections will cover the theoretical framework of the systematic literature review (Section 2), the methodology that was applied (Section 3), the results of the systematic review (Section 4), and a conclusion and discussion of the results (Section 5).

2. Theoretical Framework

2.1 Early Mathematics Education

Early mathematics learning is important for later school success [1]. Fortunately, young children are eager to learn mathematics and have a natural, spontaneous interest in mathematical ideas [3,15]. They also possess a wide variety of mathematical competencies in different mathematical subdomains, such as number knowledge and spatial competence [16]. Instruction in early childhood education should capitalize on children's natural interest in mathematics and their already acquired mathematical competencies by providing early mathematics instruction in multiple mathematics subdomains [17]. Frye and colleagues [17] distinguish among five subdomains for early mathematics instruction: number and operations, geometry, patterns, measurement, and data analysis. The subdomain of *number and operations* consists of subitizing (e.g., immediately recognizing the total number of a set of three items and labelling it with the appropriate number word "three"), counting (e.g., counting a set of eight objects), magnitude comparison (e.g., comparing the magnitude of different sets of items, such as comparing a collection of nine items versus a collection of six items and indicating the first set of items as the largest one), using numerals to quantify collections (e.g., labelling a collection of 10 items with the number word "10"), and simple arithmetic problems (e.g., adding two collections of three items). *Geometry* entails the recognition, naming, comparison, and combination of shapes (e.g., recognizing and appropriately naming a square). *Patterns* refer to identifying, extending, correcting, and creating mathematical patterns (e.g., extending an AB pattern). *Measurement* involves the comparison of objects in terms of length, volume, and time and the use of both informal (i.e., nonstandard) and formal (i.e., standard) units and tools for measuring these objects (e.g., measuring the width of a desk by counting how many “hands across” it is). Finally, *data analysis* entails collecting and organizing information and presenting this information graphically (e.g., recording the number of markers versus the number of crayons versus the number of colored pencils and presenting these numbers in a table or figure).

Unfortunately, international studies show that instruction in the domain of early mathematics is limited in terms of both frequency and content, and that there is considerable variability in the mathematics learning opportunities provided in preschool [3,18]. This low frequency and poor quality of mathematics instruction in preschool is likely due to the lack of resources available to early childhood teachers, who are trained as generalists and receive little specific training in the domain of mathematics [19]. Research suggests that early childhood teachers generally find early mathematics to be a difficult subject [20] and that they are uncertain about how to best support young children’s early mathematics learning [16]. In addition to this, early childhood teachers are tasked with addressing many curricular areas, which leaves limited time to devote to mathematics specifically, and teachers’ preference for supporting the other curricular areas means they often avoid or skip early mathematics instruction in favor of the other areas, such as early literacy [21]. When early childhood educators do provide mathematical learning opportunities, they tend to focus on the subdomain of number and operations, and spend only limited time to the other subdomains [2,3,22]. This is likely due to the scarcity of curricular options and materials that address topics beyond number and operations [23]. These findings are of serious concern as both the amount and the content of mathematical input in preschool are related to children's later mathematics learning and achievement [18,24].

A growing body of literature recognizes the potential of ET for stimulating learning, also in the domain of early mathematics (e.g., [8,14]). Unlike non-digital educational materials, ET can interact with the learner offering unique opportunities for supporting learning and instruction, also referred to as "affordances" [25]. These affordances include features such as immediate feedback and adaptivity (i.e., the capacity of ET to adapt to the differing abilities of individual children) [25]. As such, ET can complement the role of the teacher by providing ample and rich mathematical learning opportunities and, in doing so, has the potential to help early childhood teachers deliver frequent high-quality mathematics instruction in the different mathematics subdomains.

2.2 Effectiveness of ET

2.2.1 Approaches towards investigating ET effectiveness

Systematic reviews and meta-analyses (e.g., [26,27]) underscore the effectiveness of ET for improving learning outcomes in learners. However, there is a large heterogeneity in studies investigating ET effectiveness in terms of design and conditions which relates to the different approaches adopted in these studies, i.e., the media comparison approach and the value-added approach [28]. A first approach is the *media comparison approach,* which is defined by Mayer [28] as comparing learning with one medium (e.g., tablet computer) versus with another medium (e.g., paper-and-pencil or desktop computer). However, relying on the well-known media-debate [29], it is argued that not the medium *as such* makes a difference for learning. Thus, it is somewhat fruitless to ask whether computers are better than textbooks or whether tablet computers are better than desktop computers as instructional media [28]. Rather, the effects found in media comparison studies might be attributable to other, uncontrolled differences between the conditions, such as the instructional method that is introduced along with the medium (e.g., game, slide presentation) [29]. In real settings, the digital medium is always confounded with curriculum content, instructional methods, and other elements. ET should therefore be considered as a "package" of diverse elements [5,29]. As such, it might be more accurate to redefine and broaden the definition of media comparison studies to studies comparing an ET condition to a non-ET condition or another ET condition.

A second approach is the *value-added approach* which, along the definition of Mayer [28], involves the systematic comparison of the effectiveness of at least two versions of the same ET that only differ with regard to one specific feature of the ET (e.g., feedback, interactivity, adaptivity, etc.) which is systematically manipulated. These studies analyzing specific features in the ET are increasingly being complemented with studies systematically investigating different types of ET implementation that might improve learning. In line with the former studies, these studies compare the effectiveness of two different types of implementation of the same ET that only differ with respect to one specific feature (e.g., a condition of ET implementation without teacher scaffolding versus a condition of ET implementation with additional teacher scaffolding) and can therefore also be considered as studies following a value-added approach. Given their controlled research design and distinct research questions, value-added studies address the major problem of the media comparison approach, i.e., that it is not the medium as such that makes a difference for learning and that other confounding variables might explain the observed differences between the ET versus non-ET conditions.

The differences between the media comparison versus value-added approach are clearly exemplified in the recent meta-analysis of Clark and colleagues [26]. Their meta-analysis revealed that in studies adopting a media comparison approach, digital game conditions were generally more effective than non-game conditions for improving students' learning outcomes. Studies following a value-added approach complemented these findings as they demonstrated that significant learning benefits were associated with augmented game designs compared to the standard versions of these games. For instance, enhanced scaffolding in digital games (e.g., intelligent agents, personalized scaffolding based on students' needs or interests, etc.) significantly improved their effect on learning outcomes compared to the standard versions of these games (i.e., no or only limited scaffolding).

2.2.2 ET Effectiveness in Early Mathematics Education

Research interest in the effectiveness of ET for supporting early mathematical development is increasing, and the first attempts have been made to synthesize this growing body of research into a literature review ([9,10,11,12,13,14]). In line with reviews in older children (e.g., [5,6,7]) these literature reviews point to the potential of ET for improving young children's mathematical development. Notwithstanding their importance, these reviews suffer from theoretical and methodological weaknesses as they are outdated (i.e., [9,10]), especially taking into account the evolutions in ET applications, focus on a specific subgroup of children (i.e., [11,12]), or are not systematically conducted, and thus, not comprehensive (i.e., [9, 10,12,13]). The recent review of Griffith and colleagues [14] addresses these major concerns, but is limited in terms of scope (i.e., only 15 included studies on mathematics) and in terms of depth of the analysis, as it does not distinguish between studies adopting a media comparison versus a value-added approach – a criticism that also applies to all previous literature reviews in the domain.

2.3 The Present Study

Young children's early mathematical competencies are vital for their later educational success [1], but early mathematics instruction tends to occur rather infrequently in preschool and mainly focuses on the domain of number and operations (e.g., [3]). Although research provides increasing evidence that ET can be an effective tool to address this problem (e.g., [14]), previous literature reviews synthesizing this growing body of evidence suffer from several weaknesses. We aimed to address these weaknesses by conducting a systematic review of the research literature on the effectiveness of ET in the domain of early mathematics education, focusing on both children with and without special educational needs, including the most recent studies on the topic, and critically analyzing the findings coming from studies adhering to a media comparison approach versus studies following a value-added approach. In our review, we addressed three research questions (RQ's).

First, we analyzed the findings of studies adhering to a media comparison approach on the basis of RQ1: Is ET effective in the domain of early childhood mathematics education?

Since there is a large heterogeneity across media comparison studies in terms of research design and conditions, also referred to as the "control group problem" [30], we distinguished between five different subgroups of media comparison studies in terms of differences in medium (i.e., hardware) and content domain (e.g., mathematics) between the intervention and control condition(s). A first subgroup of media comparison studies compares the effectiveness of one medium to a different medium, focusing on the same content domain (e.g., comparing the effects of digital storytelling versus traditional storytelling in the domain of early mathematics). A second subgroup of media comparison studies compares the effectiveness of the same medium in conditions targeting a different content domain (e.g., comparing the effects of a game in the domain of early mathematics to a game in the domain of early literacy, using the same medium). A third subgroup of media comparison studies compares the effectiveness of the same medium in conditions targeting the same content domain (e.g., comparing two different early mathematics games, using the same medium). In a fourth subgroup of media comparison studies, the conditions differ both in terms of medium and in terms of content domain (e.g., comparing an ET condition in the domain of mathematics to a business-as-usual control condition, in which no ET, nor mathematical learning activities are provided). A fifth subgroup of media comparison studies does not provide sufficient information for identifying the medium and/or content domain applied in the control condition(s) (i.e., business-as-usual, without further specifications).

Second, we analyzed the findings of studies adhering to a value-added approach on the basis of RQ2: Which features of the ET and the ET implementation are associated with the effectiveness of ET in the domain?

Third, as studies on the effectiveness of ET in the domain of mathematics conducted in older children frequently take into account child characteristics that might be associated with its effectiveness (e.g., [31,32]), we analyzed the findings of both media comparison and value-added studies in terms of RQ3: Which child characteristics are associated with the effectiveness of ET in the domain?

3. Method

We conducted a systematic literature review [33] to answer our research questions. We started our systematic literature review by defining a review protocol specifying the methods to be used to perform the review [34], including strategies for (1) the literature search and selection process, (2) analysis and synthesis, and (3) quality appraisal, which will each be discussed in turn below.

3.1 Literature Search and Selection Process

Four databases were browsed (i.e., ERIC (Ovid version), Scopus, LearnTechLib, and Web of Science) using one combination of search terms, that is, *((preschool* OR kindergarten* OR “early childhood”) AND (ICT OR "education* technology" OR "information and communication* technology" OR digital* OR computer* OR electronic*)*

AND (math))*. The search yielded a total of 1128 hits[1]. Next, we narrowed down the search using filters: (1) peer-reviewed; (2) language: English; and (3) document type: journal article (published or in press). We also excluded duplicates, resulting in a total of 331 articles. The dataset was further reduced using five inclusion and exclusion criteria as shown in Table 1.

Table 1

Inclusion and Exclusion Criteria

Criterion	Included	Excluded
Actual use of educational technology	The article focuses on the actual use of educational technology to support the learning process of the learner(s).	The article does not focus on educational technology, e.g., using technology in the pre- and the post-test, but not as part of the intervention; not for supporting or stimulating the learning process of the learners.
Domain of mathematics	The article focuses on the stimulation of the development of mathematical competencies of learners through the use of educational technology.	The article does not focus on the domain of mathematics, e.g., focus on stimulating development in another content domain with mathematics intervention in control condition.
In institutional educational setting	The research is conducted in an institutional educational setting, e.g., a school context, including university laboratories.	The research is not conducted in an institutional educational setting, e.g., at home.
Education at the preschool and/or kindergarten level	The article addresses education at the preschool (= pre-kindergarten) and/or kindergarten level, defined as institutionalized education before the start of formal education, without specific age criteria[2].	The article addresses education at other levels, such as formal education (primary and/or secondary education), higher education (e.g., teacher training), or adult education.
True experimental or controlled quasi-experimental study design	The article reports on a true experimental study or a controlled quasi-experimental study.	Reviews, meta-analyses, theoretical papers, case studies, multiple baseline or multiple probe studies, correlational studies, and descriptive studies.

Note. Reviews and meta-analyses are excluded on the basis of our last inclusion criterion. We integrated these reviews and meta-analyses in the theoretical framework of this study (Section 2.2.2: ET Effectiveness in Early Mathematics Education).

[1] Searched in *abstract* (i.e., ERIC, Scopus and LearnTechLib) or on *topic* (i.e., Web of Science) only.

[2] The ages of children at the start and the end of preschool education differ among countries. In most European countries and in the USA, children are 6 years old when they finish preschool education and enter primary education. But, for instance in Northern Ireland, children start formal schooling at age 4, whereas Finnish children enter formal education at age 7.

The first author applied the inclusion criteria to the title and abstract of each article, and next to the entire text of the 130 remaining articles. In case the full-text of the article was not available online, the author(s) were contacted with a full-text request. However, nine full text articles could not be retrieved: four authors had outdated or missing correspondence information, and five authors did not respond. After application of the inclusion criteria to the 121 available full text articles, 46 articles were retained. Finally, additional relevant articles were identified by means of snowballing, i.e., screening the reference list of the included articles in view of other relevant articles [35]. This led to seven additional articles meeting our inclusion criteria, resulting in a total of 53 included articles indicated with an asterisk (*) in the reference list [36-88]. Figure 1 shows a flowchart of the literature search and selection process according to PRISMA guidelines [89].

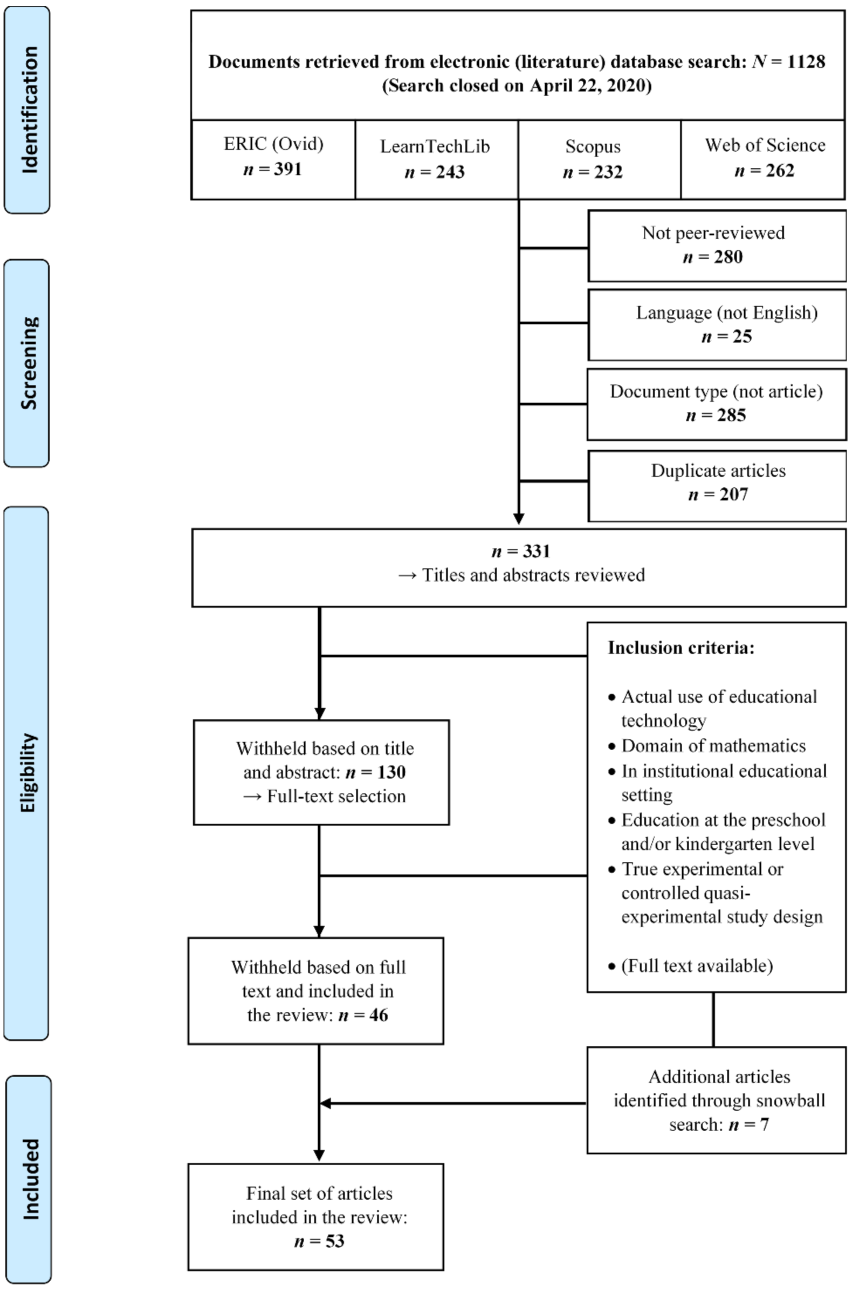
To increase the reliability of our review, a second researcher conducted the same literature selection process parallel to the first author [34]. First, the two researchers independently coded a sample (*n* = 13) of the retrieved articles. After this, their scores were compared, and through discussion, discrepancies related to the interpretation of the criteria were resolved. Next, the two reviewers evaluated a new and randomly selected sample of 34 of the 331 articles (10%). An interrater reliability of Cohen's Kappa = 1 was achieved, reflecting full agreement [90].

3.2 Analysis and Synthesis

We followed a narrative approach to analyze the data [34]. We first conducted a within-case analysis, with the article as the unit of analysis [91]. The articles were summarized in an analysis scheme, including: (1) general information (country, content area of mathematics, study design, participants, sample size, number of conditions, activities in intervention condition(s) and control condition(s), dependent and independent variables, instruments, and results), (2) the effectiveness of ET (RQ1), (3) the features of ET and ET implementation investigated (RQ2), and (4) the child characteristics investigated (RQ3). A condensed version of the analysis scheme with an example item can be found in Appendix A. Finally, we executed a cross-case analysis, comparing the articles in view of research-related patterns [91]. Article analysis was performed by the first author, with a sample of 10% of the articles additionally being analyzed by a second researcher, revealing similar results.

Figure 1

Flowchart of Literature Search and Selection Process



3.3 Quality Appraisal

Risk of bias within the included studies was assessed with the Cochrane's risk of bias tool for randomized trials [92], focusing on only categories relevant to educational research [14]. We rated both true experimental and controlled quasi-experimental studies on (1) the randomization process; (2) missing outcome data; (3) measurement of the outcome; and (4) selection of the reported result. Ratings of high risk of bias, low risk of bias, or some concerns were assigned for each domain as well as for the study as a whole. An overall low risk of bias score indicated a low risk of bias for all domains; a score of some concerns indicated some concerns in one to three domains and no high risk of bias for the other domain(s); a high risk score indicated some concerns in all domains or a high risk of bias in at least one domain. A randomly selected sample of 10% of the articles was coded for risk of bias independently by two coders. An interrater reliability of Cohen's Kappa = 1 was achieved, reflecting full agreement [90].

4. Results

4.1 Descriptives

The 53 included articles reported 54 different studies relevant for our review. The total number of participants across studies was 8632 with one study not reporting the number of participants. Twenty-six studies were conducted in Europe (including Turkey), 19 in North America, seven in Asia, one in Oceania and one in South America. In terms of study design, we only included studies adopting a true experimental or a quasi-experimental design with a control group (i.e., controlled quasi-experimental studies), as only these studies allow conclusions on the effectiveness of ET [93]. Twenty-six studies followed a true experimental design, meaning that (1) they had at least one experimental and one control condition, (2) there was a researcher-manipulated variable (intervention), and (3) the subjects (units of analysis) were randomly assigned to either the intervention or the control condition [94]. The other 28 studies adopted a controlled quasi-experimental design, which means that they adhered to the first two criteria but did not apply full randomization when assigning subjects to conditions (e.g., random assignment of classes and not subjects to conditions; cf. [95]). Of the 54 studies, 51 studies only relied on quantitative methods, whereas three studies combined both quantitative and qualitative methods (i.e., mixed methods design). Finally, regarding the different mathematics subdomains, 45 studies focused on one specific mathematics subdomain, whereas nine studies focused on multiple subdomains. The vast majority of studies (*n* = 48) focused on number and operations, 10 addressed geometry, seven addressed patterns, five focused on measurement and two addressed data analysis. See Appendix B for an overview of the study descriptives.

4.2 Risk of Bias Within Studies

Seventeen of the 54 studies (31%) were at high risk of bias overall: seven raised some concerns in all domains, nine were at high risk of bias in one domain, and one was at high risk in two domains. High risk of bias ratings were given on the randomization process (*n* = 3), missing outcome data (*n* = 7) and measurement of the outcome (*n* = 1). Thirty-seven studies raised some concerns overall: 28 raised some concerns in three domains and nine raised some concerns in two domains. See Appendix B for the result of the risk of bias assessment for each study. As no systematic differences were observed between the results reported by studies with a high risk of bias versus studies raising some concerns, we did not distinguish between studies differing in risk of bias in our analyses. Since for all studies included in the review at least some concerns can be formulated, their results should be interpreted with caution [14].

4.3 Narrative Synthesis of Studies

A summary of the design and results of the studies is provided in Appendix C. Intervention conditions and control conditions are categorized according to the review's focus, with only conditions including ET and focusing on the domain of mathematics defined as intervention conditions and all other conditions defined as control conditions. Note that this may differ from the original authors' words, as is the case when they defined a non-ET condition in the domain of mathematics as an intervention condition. It should also be noted that in all 54 studies, effectiveness was conceptualized exclusively in terms of enhancing cognitive learning outcomes in children in the domain of early mathematics, ignoring potential motivational or efficiency outcomes (e.g., time management).

4.3.1 Effectiveness of ET in General: Media Comparison Studies

Of the 54 studies, nearly all studies (*n* = 52) followed the media comparison approach. To answer RQ1, we analyzed the effectiveness of ET as reported by these studies. Given the large heterogeneity in the design and conditions of media comparison studies, as outlined above, we distinguished between different types of control conditions, taking into account differences in medium (i.e., hardware) and content domain as compared to the intervention condition(s). We discuss their results separately. Note that one study can have multiple (types of) control conditions and thus can be discussed more than once in what follows.

A first subgroup of media comparison studies (*n* = 20) compared the effectiveness of one medium to a different medium, focusing on the same content domain (i.e., mathematics) (#9; #12; #15; #16; #18; #19, #20; #22; #23; #24; #25; #26; #31; #35; #39; #48; #50; #52; #53; #54). Seventeen of these studies compared the effectiveness of ET to non-digital media (e.g., digital versus traditional storytelling) (#12; #15; #16; #18; #19, #20; #22; #24; #26; #31; #35; #39; #48; #50; #52; #53; #54), with two studies having two non-digital control conditions (#48; #54). Of these studies, a large portion (*n* = 12) reported a positive intervention effect (#15; #16; #18; #24; #26; #31; #35; #39; #48; #50; #52; #53), indicating that the intervention including ET was more beneficial for enhancing children's mathematical competencies than the instruction using a non-digital medium. Effect sizes ranged from small to large. Another three studies reported mixed findings: positive effects for some mathematical outcomes when compared to the non-digital control condition and no effects for other outcomes (#12; #20; #54). Two studies observed no differences between conditions (#19; #54) and two studies found that the ET condition was less effective than the control condition (#22; #48). Additionally, four studies compared two different ET conditions (#9; #23; #25; #26). Of these studies, two compared the effectiveness of computers versus tablets, using the same software, and both found that children in the tablet condition outperformed children in the computer condition (#25; #26). The other studies compared the effectiveness of a numerical training program using a digital dance mat versus a numerical training program using tablets (#9) and the effectiveness of tablets versus the interactive whiteboard (#23) and both found mixed results.

A second subgroup of media comparison studies (n = 11) compared the effectiveness of the same medium in conditions targeting a different content domain (#1; #5; #10; #11; #28; #30; #32; #33; #41; #44; #51). The content domains targeted in the control conditions were: literacy (n = 6), biology (n = 1), arts (n = 1), and not specified (n = 3). Four studies reported a positive effect (#1; #30; #33; #41), indicating that the ET focusing on mathematics was more beneficial for enhancing mathematical competencies than the non-mathematics ET condition. Effect sizes were small to large. Six studies reported mixed findings (#10; #11; #28; #32; #44; #51): positive effects for some mathematical outcomes when compared to the non-mathematics ET condition and no effects for other outcomes. One study reported no difference between conditions (#5).

A third subgroup of media comparison studies (*n* = 8) compared the effectiveness of the same medium in conditions targeting the same content domain (e.g., comparing the effect of "GraphoGame Math" on tablets versus the effect of "The Number Race" on tablets) (#7; #13; #30; #34; #35; #37; #40; #49). Of these studies, four reported a positive effect, indicating that one mathematics ET application was more effective than the other application for enhancing children's mathematical competencies (#7; #30; #35; #40). Effect sizes were small to large. Two studies reported mixed findings (#37; #49): one application was more beneficial for some mathematical outcomes when compared to the other application, but not for other outcomes. Two studies reported no effect (#13; #34).

Fourth, in none of the media comparison studies, the conditions differed both in terms of medium and in terms of content domain.

A fifth and last subgroup of media comparison studies (*n* = 18) did not provide sufficient information for identifying the medium and/or content domain applied in the control condition(s) (#2; #3; #4; #5; #8; #13; #14; #17; #21; #27; #29; #34; #36; #38; #43; #45; #46; #47). These were all studies that reported a business-as-usual control condition, without further specifications. Ten studies reported a positive effect (#2; #3; #4; #14; #17; #21; #29; #38; #43; #47) indicating that the intervention condition was more effective than the business-as-usual control condition for preschoolers' mathematical competencies. Again, effect sizes ranged between small to large. Four studies reported mixed findings (#27; #34; #45; #46): the intervention condition was more beneficial than the control condition only for some mathematics measures, and four studies found no differences (#5; #8; #13; #36).

4.3.2 Characteristics of ET and its Implementation related to Effectiveness: Value-Added Studies

For RQ2, we analyzed the results of value-added studies (*n* = 8) with respect to the features of the ET and ET implementation associated with the intervention effect. The features of the ET were investigated in four value-added studies (#1; #6; #42; #46), focusing on interactivity, meta-cognitive guidance and the instructional principles adopted in the ET. The feature of interactivity (i.e., ET systematically responding to learners' actions) was investigated in two studies (#1; #42). In both studies, children playing a digital game (interactive condition) were compared to children watching a video of a researcher playing the same game (non-interactive condition, without possibility to alter the pace or outcome of the game). In the first study, there was no statistically significant difference in performance between participants in the interactive condition and their counterparts in the non-interactive condition on measuring tasks (#1). In the second study, preschoolers' performance on a quantity mathematics task only improved after watching the instructional video, but not after playing the mathematics game (#42). One study investigated meta-cognitive guidance in the ET by comparing a standard version of an educational e-book in the domain of early mathematics with a version that additionally provided build-in meta-cognitive guidance during reading. However, no difference in effectiveness was found (#46). Finally, one study focused on the instructional principles used in the ET, comparing four ET supported conditions relying on: (1) semi-structured discovery learning, (2) structured discovery learning, (3) structured discovery learning and explicit practice (direct instruction), and (4) unstructured practice. No significant difference between the four conditions was found (#6).

Four value-added studies analyzed the potential contribution of features of the ET implementation to its effectiveness (#17; #24; #41; #50). With respect to grouping structure, which was investigated in one study, children working individually with ET outperformed children working cooperatively with the same ET on measures for high level mathematical computation (estimating, adding, subtracting) (#50). In another study, three ET enhanced conditions, one without scaffolding (i.e., support), one with help and support provided by peers, and one with teacher scaffolding, were compared. Results revealed that children from the condition with scaffolding by the teacher made most progress (#17). In a study focusing on parental support in mathematics at home in addition to educational game play in the classroom (#41), no association with ET effectiveness was found when compared to a condition providing educational game play in the classroom using the same game, but without parental support (#41). When comparing two forms of mathematics app implementation, i.e., (1) implementing ET during free play, as a supplement to regular mathematics instruction, extending the daily instructional time devoted to mathematics, and (2) implementing the same ET during regular mathematics instruction, retaining the original instructional time devoted to mathematics, no significant differences were found (#24).

4.3.3 Child Characteristics related to Effectiveness: Media Comparison and Value Added Studies

For RQ3, we analyzed the child characteristics associated with ET effectiveness in both media comparison and value-added studies. Child characteristics were investigated in 24 media comparison studies (#4; #8; #11; #18; #20; #21; #23; #25; #26; #28; #32; #35; #36; #37; #38; #39; #40; #43; #44; #45; #49; #51; #52; #53). Eight media comparison studies examined gender as a potential associated variable (#8; #21; #25; #26; #28; #38; #39; #40), with only one study observing an association with ET effectiveness, favoring girls (#40). Children's age was investigated in four studies (#18; #25; #35; #40). Although three studies found no association between age and ET effectiveness (#25; #35; #40), one study indicated that younger preschoolers improved their mathematical knowledge more than older ones (#18). Twelve studies addressed children's prior knowledge, as evidenced by their pretest scores, as a potential associated variable (#4; #20; #32; #35; #38; #39; #40; #44; #49; #51; #52; #53). However, their findings remain indecisive as two studies did not find an association with ET effectiveness (#4; #44), whereas ten studies did find such an association (#20; #32; #35; #38; #39; #40; #49; #51; #52; #53). Moreover, in some studies children with lower prior achievement (#32; #35; #38; #39; #49; #51) and in other studies children with medium or high prior achievement (#20; #40; #52; #53) benefitted most from the ET. The skill level or performance of the children in the digital learning environment was investigated in two studies (#21; #36). Both studies reported that children who reached the upper levels in the game had higher gain scores at post-test than children who did not reach these levels. Three studies investigated the amount of ET usage of the children and reported mixed findings (#21; #37; #49). Whereas two studies observed a positive association between (a) the total number of activities and time spent in the interventions and (b) mathematics performance after the intervention (respectively #49; #21), another study observed no association between minutes or sessions played and gain scores on a mathematics achievement test (#37). Of the four studies investigating race/ethnicity as a potential associated factor (#21, #38,# 39, #40), one study did find such an association: the ET intervention effect was greater for non-Caucasian children (i.e., Hispanic, African American, Asian and multi-racial) compared to Caucasian children (#39). One study investigated the association between children's effort during educational game play and ET effectiveness, and found that individual differences in effort predicted children's improvements in number line estimation at posttest (#32). Finally, other child characteristics that were investigated, but were found not to be associated with ET effectiveness, were: vocabulary (language) scores (#11), socio-economic status (#23), memory (#23), children's at risk status for learning disabilities (#43), and verbal ability (#45).

One value-added study investigated child characteristics (#42). In line with the media comparison studies, this study found an association between ET effectiveness and the child characteristics of prior knowledge, performance in the ET, and age. Specifically, children with higher prior knowledge and children who made fewer errors while playing the game, benefited most from ET. In terms of age, an interaction effect was found with interactivity: younger children only learned from a game when they watched the game being played by someone else (non-interactive condition) rather than when playing the game themselves (interactive condition), while older preschoolers improved in neither condition. Character familiarity (i.e., the extent to which the child is familiar with the characters in the game), was also investigated in this study, but was found not to be correlated with children's learning outcomes after the intervention (#42).

5. Conclusions and Discussion

Despite the general agreement on the importance of children's early mathematical skills for their later mathematical development [1], mathematics instruction in preschool is limited [3]. ET may be a valuable tool to provide frequent and high-quality mathematics learning opportunities to preschoolers (e.g., [8,14]). Reviews and meta-analyses in older children and students point to the effectiveness of ET for improving mathematical learning outcomes (e.g., [5,6,7]). Similarly, literature reviews focusing on early childhood education underscore the potential of ET for supporting early mathematical development as well [9,10,11,12,13,14]. However, as these reviews in the domain of early childhood education suffer from serious weaknesses, a systematic and comprehensive literature review on the topic is currently lacking. Such a review is needed to inform research, on the gaps in the existing knowledge and valuable avenues for future research, as well as educational practice, on effective tools for supporting young children's mathematical development and effective approaches for designing and implementing these tools. We therefore addressed their weaknesses by conducting a systematic and comprehensive literature review on the topic, focusing on both children with and without special educational needs, and including the most recent studies on the topic. Moreover, we distinguished between the insights coming from media comparison studies versus value-added studies in the domain. In general, we found that almost all studies on the topic adopted a media comparison approach whereas only a small minority of studies adhered to the value-added approach. Of the media comparison studies, about one third compared conditions with a different medium but focusing on the same content domain. About one third did not provide sufficient information for determining the medium and/or content domain in the control condition(s). The other studies either compared the effectiveness of the same medium in conditions targeting a different content domain or the effectiveness of the same medium in conditions targeting the same content domain. In what follows, the major findings of the media comparison and value-added studies in relation to each research question as well as their implications for future research and educational practice will be discussed (Section 5.1). We end with a reflection on the limitations of the reviewed studies and of the current systematic review (Section 5.2).

5.1 ET Effectiveness in Early Childhood Mathematics Education

5.1.1 RQ1: Effectiveness of ET in General

To answer RQ1, we analyzed the effectiveness of ET as reported by media comparison studies. About one third of the media comparison studies compared conditions with a different medium but focusing on the same content domain. Most of them compared an ET condition to a non-ET condition. Nearly all these studies found that the ET was at least as effective as or even more effective than the support provided in the non-ET condition for one or more outcomes in the domain of early mathematics. This suggests that ET can be an effective tool for supporting preschoolers' early mathematical development. However, in line with the media-debate [29], we caution that it is not the medium as such that makes a difference for learning, as there is nothing inherent in the medium or technology that automatically guarantees learning. Rather, the positive effects reported by these media comparison studies might be attributable to other, uncontrolled differences between the conditions, such as the specific method (i.e., ET program) being adopted [29]. Indeed, when comparing two ET conditions in the domain of mathematics, using the same medium but a different method, it was found that also the specific ET program applied in the domain of mathematics can make a difference for learning. Moreover, when comparing two ET conditions, using the same medium, but focusing on a different content domain (e.g., literacy), more than half of the studies reported no differences or mixed findings. This is surprising given that the children in the intervention condition received (extra) instruction in the domain of mathematics, whereas the children in the control condition did not. Again, it might be that additional uncontrolled variables such as child characteristics or features of the ET applications and their implementation that differed between conditions, confounded the results [29]. Against this background, we argue that to further advance the field, future media comparison studies should not be designed so as to compare the effectiveness of different media (i.e., different medium same content domain), and should minimize the number of differences between the conditions being compared, by comparing the effectiveness of two or more different methods using the same medium, within the same content domain.

Additionally, as was also observed in previous reviews (e.g., [26]), about one third of the media comparison studies provided no or only sparse descriptions of the activities in the control conditions (i.e., business-as-usual, without further specifications). This is problematic as no strong, unambiguous conclusions can be drawn on the basis of their results given the multitude of possible differences that might have existed between the intervention and control conditions. Future media comparison studies should provide more elaborate descriptions of the different conditions and adopt a meaningful control condition (i.e., same medium, same content domain, different method) to support informed interpretations of their results and to allow comparisons across studies [26]. Moreover, given the concerns related to media comparison research, we argue that these studies need to be complemented with more well-designed and controlled studies investigating how the ET should be designed and implemented in order to be effective, a question typically addressed by studies adopting a value-added approach.

5.1.2 RQ2: Characteristics of ET and its Implementation related to Effectiveness

For RQ2, we analyzed the results of value-added studies on the features of the ET and the ET implementation that are associated with the intervention effect. Contrasting the media comparison studies in our review, studies adhering to the value-added approach were scarce. Therefore, insights on the ET and ET implementation features that are associated with ET effectiveness is early mathematics education are limited and should be interpreted with caution as no strong claims can be made on the basis of this limited number of studies.

Regarding ET features, interactivity, meta-cognitive guidance, and the instructional principles adopted in the ET were investigated. While these ET features have been found to contribute to the effectiveness of ET for enhancing learning in older children in the domain of mathematics (see for instance [96] for meta-cognitive guidance), none of these features were found to be associated with ET effectiveness in early mathematics education. A possible explanation relates to the young age of the children and their limited cognitive capacities. Based on cognitive load theory [97], it is suggested that instruction often imposes unnecessary cognitive load on learners hampering learning. This especially applies to the use of ET as these technologies are replete with affordances that can facilitate learning but can also serve as a distraction to many students [25]. As such, it may be that the investigated features of the ET placed undue burdens on young children's cognitive capabilities. For instance, as for interactivity, it might have been the case that children had to devote a significant portion of their limited working memory resources to the physical requirements of manipulating the ET during game play, which may negatively impact their ability to attend to the mathematical content. Conversely, children in the non-interactive condition did not have to focus on the physical manipulation of the game, and therefore, were able to devote more working memory resources to acquiring the mathematical content [36]. Likewise, for meta-cognitive guidance, the extra information and tools provided in the ET might have caused a cognitive overload in preschoolers. Future studies are needed to test this hypothetical explanation by systematically manipulating and investigating features of the ET that might reduce cognitive load in preschoolers during ET use, relying on the framework of Mayer on multimedia principles [25]. Moreover, in terms of instructional principles, given the specificity of early childhood education (e.g., play-based pedagogy, primarily learning activities focusing on multiple curricular domains in an integrated way), it might be promising for future studies on the topic to investigate other instructional principles in the ET that are more in line with this pedagogy, such as different game features (e.g., feedback, repetition, adaptivity, challenge, reward, etc.).

Related to ET implementation, the contribution of grouping structure, scaffolding by the teacher, parental support, and the integration of ET as a supplement to versus as a part of regular mathematics education, were investigated. Two of these features were found to contribute to ET effectiveness. Specifically, ET was found to be more effective for learning when the children were provided with support by the teacher during ET use [52] and when used individually rather than cooperatively [84]. This second finding is surprising given the growing literature on the positive effects of cooperation and collaboration using ET [25], also in the context of early mathematics education (e.g., [49]). A possible explanation might be that, given the young age of the children, they did not yet acquire the necessary meta-cognitive, coordination and communication skills to recognize each other’s mistakes and to give valuable feedback and support to one another [84]. This might imply that in order for ET based collaborative learning in early mathematics to be effective, teacher scaffolding is needed, which is also recognized in the Computer Supported Collaborative Learning (CSCL) literature (e.g., [49,98]). As such, future studies addressing the effectiveness of teacher scaffolding during collaborative ET use in early mathematics education are needed [98,99].

We conclude that many unaddressed questions about the design and implementation of ET in view of ET effectiveness remain. To further advance the field, carefully designed and controlled value-added studies are needed to develop our insight into the elements that enhance learning and learning processes from ET in this specific age group. Such studies would not only further scientific knowledge on the topic of ET effectiveness in early childhood mathematics education, but would also provide building blocks for designing and implementing effective technology-enhanced learning environments in early childhood education, and as such enhance the quality of classroom instruction and young children's development in the domain of mathematics.

5.1.3 RQ3: Child Characteristics related to Effectiveness

For RQ3, we analyzed the child characteristics associated with ET effectiveness in both media comparison studies and value-added studies. Both types of studies revealed that especially children's skill level or performance in the ET and their prior knowledge are important to take into account when considering ET effectiveness in the domain of early mathematics. For the other child characteristics, no unequivocal evidence (i.e., age, gender, amount of ET use and race/ethnicity) or no evidence (i.e., vocabulary, at risk status for learning disabilities, socio-economic status, memory, and verbal ability) of an association with ET effectiveness was found.

With respect to skill level or performance in the ET, our review revealed that ET was most effective when children reached the upper levels in the ET or when they made fewer mistakes. A first possible explanation for this finding is that children reaching the upper levels in the ET also practiced more using the ET (time was not strictly controlled in these studies), equipping these children with more learning opportunities, which may have led to larger gains on posttest. A second explanation relates to the relevance of the content of these learning experiences and the structure of the ET in terms of how the content is organized. Possibly, the mathematical contents which are assessed on posttest are only encountered and practiced in higher ET levels.

Turning to children's prior knowledge, our review revealed that children's prior knowledge was associated with ET effectiveness, although research remains inconclusive as to whether children with high, medium or rather low prior knowledge benefit most from ET. A possible explanation for these mixed findings relates to the features of the ET or ET implementation that might have differed between studies, such as the ET feature of adaptivity. Adaptive technology presents information to the learner that is contingent on the learner's prior knowledge, behavior, and/or other characteristics, and as such, can take children's prior knowledge level into account [25]. Therefore, adaptive ET is considered better than non-adaptive ET, and is considered to be especially beneficial for children with high or low prior knowledge (as compared to medium prior knowledge). Given the importance of prior knowledge for learning, future studies should further look into the differential pattern of effectiveness of ET according to children's prior knowledge. For instance, future studies on the topic should investigate and compare the effectiveness of adaptive ET for different groups of children in terms of prior knowledge. Such studies would not only further scientific knowledge on the topic, but would also allow educational practitioners and software developers to choose or design for each child the most effective pedagogical approach.

5.2 Limitations

A number of limitations, both of our systematic literature review and of the studies included in our systematic literature review, should be acknowledged. We first discuss the limitations of our systematic review. To address the weaknesses of previous reviews on the topic, we distinguished between the findings of media comparison studies versus value-added studies given their distinct research questions and designs. This distinction allowed us to only synthesize the results of studies with a similar design and research question, and thereby, to meaningfully analyze and interpret their results. However, there was still a large heterogeneity in the media comparison studies in terms of design and conditions. Due to this “control group problem”, it is impossible to compare the results of the effectiveness of ET for supporting learning in the different media comparison studies as there is no common baseline for such a comparison [30]. We therefore further distinguished between different types of media comparison studies, taking into account differences between conditions in terms of medium and content domain. We acknowledge that other differences may have existed between the conditions and may have contributed to the reported effects, such as the specific instructional methods being adopted [29]. However, given the small sample of studies, we decided to not further split up the studies into more subcategories of media comparison studies. For future review studies on the topic, including a larger number of studies, it may be worthwhile to adopt a more fine-grained approach when analyzing the results of media comparison studies by also taking other potential differences between conditions into account, such as the specific instructional methods adopted, the mathematics subdomains and contents being addressed, the types of tasks presented in the ET, and the characteristics of the participants included.

We now turn to the limitations of the included studies. First, in terms of study quality, it was found that for all studies included in the review, at least some concerns regarding their quality could be formulated. This is of serious concern, as the study design quality of studies assessing ET effectiveness might affect the results of these studies [100]. Moreover, as also observed in previous reviews (e.g., [14,26]), many studies had incomplete reporting of study methods, making it difficult to assess their study quality and often leading to lower scores on their quality assessment. Future studies should therefore be more rigorously designed and provide more information on at least: the randomization process, the reporting and handling of missing outcome data, measurement of the outcome, and selection of the reported result.

Second, with respect to the specific early mathematics subdomains investigated in the studies [17], the vast majority focused on number and operations. However, the subdomain of number and operations already receives most attention in preschool while the other subdomains (i.e., geometry, patterns, measurement and data analysis), receive limited attention in preschool [2,3,22]. A possible explanation for this predominant focus on number and operations in both research and educational practice relates to the scarcity of educational resources addressing topics beyond number and operations [23]. This is problematic given the importance of also these other mathematical subdomains [17]. To support early childhood educators to address these other subdomains, and to foster scientific research on the topic, educational software designers should design and develop ET programs in these other subdomains. Accordingly, future research needs to investigate the effectiveness of programs focusing on other subdomains, rather than almost exclusively focusing on the subdomain that already receives most attention in preschools.

Third, the effectiveness of ET investigated in the studies referred solely to cognitive learning outcomes. However, several scholars have stressed the possibilities of ET to also enhance motivational outcomes and efficiency outcomes in learners [27,101]. Although some studies qualitatively reported children's engagement and motivation during ET use [40,43,65], all of which reported a high level of enjoyment of the children during ET use, the effect of ET on their motivation was not analyzed. Given the importance of motivation to continue interacting with the ET, and consequently, to learn, research investigating the effect of ET on motivation in the domain is needed. However, it should be noted that measuring affective outcomes (e.g., motivation, interest, self-concept) in young children is challenging [102], especially when relying on self-reported data [103]. Therefore, a multimodal approach is recommended for the assessment of affective outcomes in which self-reported data (based on questionnaires and/or interviews) are complemented with unobtrusive data collected during ET use (e.g., physiological data) [103]. Furthermore, efficiency outcomes (i.e., time management and cost-effectiveness) could be taken into account. Especially time management is considered relevant when assessing the effectiveness of ET in education (e.g., achieving more during one lesson hour), even more so because time management plays an important role in teachers' decision for adopting and implementing the ET. Future studies on the topic in younger children should also focus on efficiency outcomes, by registering and taking into account the time children spent training with the ET, in order to achieve a more comprehensive picture on the effectiveness of ET in the domain. Additionally, it should be noted that many studies did not use validated standardized instruments and most studies only assessed the effectiveness of the ET immediately after the intervention. Future studies on the topic should include validated standardized measures so as to not bias their findings as well as a delayed posttest to asses long-term effects (min. two weeks after intervention has finished). Such posttests are relevant, especially in short intervention studies, to control for the novelty effect and for positive effects as a result of intensive training [27,104].

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7. Declaration of Interest Statement

Conflicts of interest: None.

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9. References

[1] G.J. Duncan, C.J. Dowsett, A. Claessens, K. Magnuson, A.C. Huston, P. Klebanov, L.S. Pagani, L. Feinstein, M. Engel, J. Brooks-Gunn, H. Sexton, K. Duckworth, C. Japel, School Readiness and Later Achievement, Dev. Psychol. 43 (2007) 1428–1446. https://doi.org/10.1037/0012-1649.43.6.1428.

[2] C. Björklund, W. Barendregt, Teachers' Pedagogical Mathematical Awareness in Swedish Early Childhood Education, Scand. J. Educ. Res. 60 (2016) 359–377. https://doi.org/10.1080/00313831.2015.1066426.

[3] S.B. Piasta, C.Y. Pelatti, H.L. Miller, Mathematics and Science Learning Opportunities in Preschool Classrooms, Early Educ. Dev. 25 (2014) 445–468. https://doi.org/10.1080/10409289.2013.817753.

[4] A.C.K. Cheung, R.E. Slavin, Effects of educational technology applications on reading outcomes for struggling readers: A best-evidence synthesis, Read. Res. Q. 48 (2013) 277–299. https://doi.org/10.1002/rrq.50.

[5] A.C.K. Cheung, R.E. Slavin, The effectiveness of educational technology applications for enhancing mathematics achievement in K-12 classrooms: A meta-analysis, Educ. Res. Rev. 9 (2013) 88–113. https://doi.org/10.1016/j.edurev.2013.01.001.

[6] Q. Li, X. Ma, A meta-analysis of the effects of computer technology on school students' mathematics learning, Educ. Psychol. Rev. 22 (2010) 215–243. https://doi.org/10.1007/s10648-010-9125-8.

[7] J. Young, Technology-enhanced mathematics instruction: A second-order meta-analysis of 30 years of research, Educ. Res. Rev. 22 (2017) 19–33. https://doi.org/10.1016/j.edurev.2017.07.001.

[8] D.H. Clements, J. Sarama, Young children and technology: What does the research say?, Young Child. 58 (2003) 34–40.

[9] D.H. Clements, J. Sarama, The Role of Technology in Early Childhood Learning, Teach. Child. Math. 8 (2002) 202–220. https://doi.org/10.4018/978-1-7998-3383-3.ch012.

[10] D.A. Lieberman, C.H. Bates, J. So, Young children's learning with digital media, Comput. Sch. 26 (2009) 271–283. https://doi.org/10.1080/07380560903360194.

[11] T. Aydemir, Ç. Çürük, The instruction methods in teaching mathematics to preschool students with special need, TOJET 14 (2015) 632-638.

[12] A. Drigas, G. Kokkalia, M.D. Lytras, ICT and collaborative co-learning in preschool children who face memory difficulties, Comput. Human Behav. 51 (2015) 645–651. https://doi.org/10.1016/j.chb.2015.01.019.

[13] A.S. Drigas, G.K. Kokkalia, Icts in kindergarten, Int. J. Emerg. Technol. Learn. 9 (2014) 52–58. https://doi.org/10.3991/ijet.v9i2.3278.

[14] S.F. Griffith, M.B. Hagan, P. Heymann, B.H. Heflin, D.M. Bagner, Apps As Learning Tools: A Systematic Review, Pediatrics. 145 (2020) 20191579. https://doi.org/10.1542/peds.2019-1579.

[15] H.P. Ginsburg, M. Amit, What is teaching mathematics to young children? A theoretical perspective and case study, J. Appl. Dev. Psychol. 29 (2008) 274–285. https://doi.org/10.1016/j.appdev.2008.04.008.

[16] A. MacDonald, S. Murphy, Mathematics education for children under four years of age: a systematic review of the literature, Early Years. 00 (2019) 1–18. https://doi.org/10.1080/09575146.2019.1624507.

[17] D. Frye, A.J. Baroody, M. Burchinal, S.M. Carver, N.C. Jordan, J. McDowell, Teaching Math to Young Children, Educator's Practice Guide, What Works Clearinghouse (2013) [PDF-file]. https://ies.ed.gov/ncee/wwc/Docs/practiceguide/wwc_empg_summary_020714.pdf

[18] R.S. Klibanoff, S.C. Levine, J. Huttenlocher, M. Vasilyeva, L. V. Hedges, Preschool children's mathematical knowledge: The effect of teacher "math talk," Dev. Psychol. 42 (2006) 59–69. https://doi.org/10.1037/0012-1649.42.1.59.

[19] D.H. Clements, C. Copple, M. Hyson, Early childhood mathematics: Promoting good beginnings, in: Joint Position Statement of the National Association for the Education of Young Children and the National Council of Teachers of Mathematics, 2002, pp. 1-21.

[20] J.V. Copley, Y. Padrón, Preparing teachers of young learners: Professional development of early childhood teachers in mathematics and science, in: G.D. Nelson (Ed.), Dialogue on early childhood science, mathematics, and technology education, American Association for the Advancement of Science, 1999, pp.117−129.

[21] FPG Child Development Institute, The University of North Carolina at Chapel Hill, Early developments. https://fpg.unc.edu/sites/fpg.unc.edu/files/resources/early-developments/FPG_EarlyDevelopments_v9n1.pdf, 2005 (accessed 16 October 2020).

[22] D.H. Clements, J. Sarama, Early childhood teacher education: The case of geometry, J. Math. Teach. Educ. 14 (2011) 133–148. https://doi.org/10.1007/s10857-011-9173-0.

[23] D.H. Clements, J. Sarama, Learning and teaching early math: The learning trajectories approach, Routledge, New York, 2014.

[24] M. Engel, A. Claessens, T. Watts, G. Farkas, Mathematics Content Coverage and Student Learning in Kindergarten, Educ. Res. 45 (2016) 293–300. https://doi.org/10.3102/0013189X16656841.

[25] National Academies of Sciences, Engineering, and Medicine, How people learn II: Learners, contexts, and cultures, The National Academies Press, Washington, DC, 2018. https://doi.org/10.17226/24783.

[26] D.B. Clark, E.E. Tanner-Smith, S.S. Killingsworth, Digital Games, Design, and Learning: A Systematic Review and Meta-Analysis, Rev. Educ. Res. 86 (2016) 79–122. https://doi.org/10.3102/0034654315582065.

[27] P. Wouters, C. van Nimwegen, H. van Oostendorp, E.D. van Der Spek, A meta-analysis of the cognitive and motivational effects of serious games, J. Educ. Psychol. 105 (2013) 249–265. https://doi.org/10.1037/a0031311.

[28] R.E. Mayer, Multimedia learning and games, in: S. Tobias, J.D. Fletcher (Eds.), Computer games and instruction, Information Age, 2011, pp. 281–305.

[29] R.E. Clark, Reconsidering Research on Learning from Media, Rev. Educ. Res. 53 (1983) 445–459.

[30] C. Girard, J. Ecalle, A. Magnan, Serious games as new educational tools: How effective are they? A meta-analysis of recent studies, J. Comput. Assist. Learn. 29 (2013) 207–219. https://doi.org/10.1111/j.1365-2729.2012.00489.x.

[31] S. Vanbecelaere, F. Cornillie, D. Sasanguie, B. Reynvoet, F. Depaepe, The effectiveness of an adaptive digital educational game for the training of early numerical abilities in terms of cognitive, noncognitive and efficiency outcomes, Br. J. Educ. Technol. 0 (2020) 1–13. https://doi.org/10.1111/bjet.12957.

[32] S. Vanbecelaere, K. Van den Berghe, F. Cornillie, D. Sasanguie, B. Reynvoet, F. Depaepe, The effects of two digital educational games on cognitive and non-cognitive math and reading outcomes, Comput. Educ. 143 (2020) 103680. https://doi.org/10.1016/j.compedu.2019.103680.

[33] B. Kitchenham, Guidelines for performing Systematic Literature Reviews in Software Engineering, Version 2.3, EBSE Technical Report EBSE-2007-01, Keele University and University of Durham, 2007.

[34] M. Petticrew, H. Roberts, Systematic reviews in the social sciences: A practical guide, Blackwell Publishing, New Jersey, 2007.

[35] A. Sayers, Tips and tricks in performing a systemic review, Br. J. Gen. Pract. 58 (2007) 136. https://doi.org/10.3399/bjgp08X277168.

[36] *F. Aladé, A.R. Lauricella, L. Beaudoin-Ryan, E. Wartella, Measuring with Murray: Touchscreen technology and preschoolers' STEM learning, Comput. Human Behav. 62 (2016) 433–441. https://doi.org/10.1016/j.chb.2016.03.080.

[37] *I. Alghazo, O. Alsawaie, H. Al-Awidi, Enhancing counting skills of preschoolers through the use of computer technology and manipulatives, Int. J. Learn. 17 (2010) 159–176. https://doi.org/10.18848/1447-9494/cgp/v17i09/47227.

[38] *T. Alzubi, R. Fernandez, J. Flores, M. Duran, J.M. Cotos, Improving the Working Memory during Early Childhood Education Through the Use of an Interactive Gesture Game-Based Learning Approach, IEEE Access. 6 (2018) 53998–54009. https://doi.org/10.1109/ACCESS.2018.2870575.

[39] *E. Aragón-Mendizábal, M. Aguilar-Villagrán, J.I. Navarro-Guzmán, R. Howell, Improving number sense in kindergarten children with low achievement in mathematics, An. Psicol. 33 (2017) 311-318. https://doi.org/10.6018/analesps.33.2.239391.

[40] *P. Aunio, R. Mononen, The effects of educational computer game on low-performing children's early numeracy skills – an intervention study in a preschool setting, Eur. J. Spec. Needs Educ. 33 (2018) 677-691. https://doi.org/10.1080/08856257.2017.1412640.

[41] *A.J. Baroody, M.D. Eiland, D.J. Purpura, E.E. Reid, Fostering At-Risk Kindergarten Children's Number Sense, Cogn. Instr. 30 (2012) 435–470. https://doi.org/10.1080/07370008.2012.720152.

[42] *A.J. Baroody, M. Eiland, B. Thompson, Fostering at-risk preschoolers' number sense, Early Educ. Dev. 20 (2009) 80-128. https://doi.org/10.1080/10409280802206619.

[43] *Ü. Çakiroğlu, N. Taşkin, Teaching Numbers to Preschool Students with Interactive Multimedia : An Experimental Study, Cukurova University Faculty of Education Journal 45 (2016) 1–22.

[44] *U. Fischer, K. Moeller, M. Bientzle, U. Cress, H.C. Nuerk, Sensori-motor spatial training of number magnitude representation, Psychon. Bull. Rev. 18 (2011) 177–183. https://doi.org/10.3758/s13423-010-0031-3.

[45] *M.E. Foster, J.L. Anthony, D.H. Clements, J. Sarama, J.M. Williams, Improving Mathematics Learning of Kindergarten Students Through Computer-Assisted Instruction, J. Res. Math. Educ. 47 (2016) 206–232. https://doi.org/10.5951/jresematheduc.47.3.0206.

[46] *M.E. Foster, J.L. Anthony, D.H. Clements, J. Sarama, J.J. Williams, Hispanic dual language learning kindergarten students' response to a numeracy intervention: A randomized control trial, Early Child. Res. Q. 43 (2018) 83–95. https://doi.org/10.1016/j.ecresq.2018.01.009.

[47] *Z. Gecu-Parmaksiz, O. Delialioglu, Augmented reality-based virtual manipulatives versus physical manipulatives for teaching geometric shapes to preschool children, Br. J. Educ. Technol. 50 (2019) 3376–3390. https://doi.org/10.1111/bjet.12740.

[48] *T. Gerholm, P. Kallioinen, S. Tonér, S. Frankenberg, S. Kjällander, A. Palmer, H. Lenz-Taguchi, A randomized controlled trial to examine the effect of two teaching methods on preschool children's language and communication, executive functions, socioemotional comprehension, and early math skills, BMC Psychol. 7 (2019) 1–28. https://doi.org/10.1186/s40359-019-0325-9.

[49] *F. Gómez, M. Nussbaum, J.F. Weitz, X. Lopez, J. Mena, A. Torres, Co-located single display collaborative learning for early childhood education, Int. J. Comput. Collab. Learn. 8 (2013) 225–244. https://doi.org/10.1007/s11412-013-9168-1.

[50] *K. Goodwin, The impact of interactive multimedia on kindergarten students' representations of fractions, Issues Educ. Res. 18 (2008) 103–117.

[51] *K.M. Haegele, J.J. McComas, M. Dixon, M.K. Burns, Using a Stimulus Equivalence Paradigm to Teach Numerals, English Words, and Native American Words to Preschool-Age Children, J. Behav. Educ. 20 (2011) 283–296. https://doi.org/10.1007/s10864-011-9134-9.

[52] *H. Kermani, Computer mathematics games and conditions for enhancing young children's learning of number sense, Malaysian J. Learn. Instr. 14 (2017) 23–57. https://doi.org/10.32890/mjli2017.14.2.2.

[53] *B. Kramarski, I. Weiss, Investigating Preschool Children's Mathematical Engagement in a Multimedia Collaborative Environment, J. Cogn. Educ. Psychol. 6 (2007) 411–432. https://doi.org/10.1891/194589507787382016.

[54] *C. Mattoon, A. Bates, R. Shifflet, N. Latham, S. Ennis, Examining computational skills in Prekindergarteners: The effects of traditional and digital manipulatives in a prekindergarten classroom, Early Child. Res. Pract. 17 (2015).

[55] *T.S. McCollister, D.C. Burts, V.L. Wright, G.J. Hildreth, Effects of computer-assisted instruction and teacher-assisted instruction on arithmetic task achievement scores of kindergarten children, J. Educ. Res. 80 (1986) 121–125. https://doi.org/10.1080/00220671.1986.10885735.

[56] *M.H. McManis, L.D. McManis, Using a touch-based, computer-assisted learning system to promote literacy and math skills for low-income preschoolers, J. Inf. Technol. Educ. Res. 15 (2016) 409–429. https://doi.org/10.28945/3550.

[57] *Z. Nikiforidou, Probabilities and Preschoolers: Do Tangible Versus Virtual Manipulatives, Sample Space, and Repetition Matter?, Early Child. Educ. J. 47 (2019) 769–777. https://doi.org/10.1007/s10643-019-00964-2.

[58] *L.A. Outhwaite, A. Gulliford, N.J. Pitchford, Closing the gap: Efficacy of a tablet intervention to support the development of early mathematical skills in UK primary school children, Comput. Educ. 108 (2017) 43–58. https://doi.org/10.1016/j.compedu.2017.01.011.

[59] *L.A. Outhwaite, M. Faulder, A. Gulliford, N.J. Pitchford, Raising early achievement in math with interactive apps: A randomized control trial, J. Educ. Psychol. (2019). https://doi.org/10.1037/edu0000286.

[60] *S. Papadakis, M. Kalogiannakis, N. Zaranis, Comparing Tablets and PCs in teaching Mathematics: An attempt to improve Mathematics Competence in Early Childhood Education, Presch. Prim. Educ. 4 (2016) 241-253. https://doi.org/10.12681/ppej.8779.

[61] *S. Papadakis, M. Kalogiannakis, N. Zaranis, The effectiveness of computer and tablet assisted intervention in early childhood students' understanding of numbers. An empirical study conducted in Greece, Educ. Inf. Technol. 23 (2018) 1849–1871. https://doi.org/10.1007/s10639-018-9693-7.

[62] *T. Pazouki, V. Cornu, P. Sonnleitner, C. Schiltz, A. Fischbach, R. Martin, MaGrid: A language-neutral early mathematical training and learning application, Int. J. Emerg. Technol. Learn. 13 (2018) 4–18. https://doi.org/10.3991/ijet.v13i08.8271.

[63] *S. Pekarkova, E. Milkova, Spatial Skills of Preschool Children supported by Game Application, Int. J. Educ. Inf. Technol. 11 (2017) 138–142.

[64] *M. Praet, A. Desoete, Enhancing young children's arithmetic skills through non-intensive, computerised kindergarten interventions: A randomised controlled study, Teach. Teach. Educ. 39 (2014) 56–65. https://doi.org/10.1016/j.tate.2013.12.003.

[65] *N.M. Preradovic, G. Lesin, D. Boras, Introduction of digital storytelling in preschool education: A case study from Croatia, Digit. Educ. Rev. (2016) 94–105. https://doi.org/10.1344/der.2016.30.94-105.

[66] *G.B. Ramani, E.N. Daubert, G.C. Lin, S. Kamarsu, A. Wodzinski, S.M. Jaeggi, Racing dragons and remembering aliens: Benefits of playing number and working memory games on kindergartners' numerical knowledge, Dev. Sci. 23 (2019) 1–17. https://doi.org/10.1111/desc.12908.

[67] *G.B. Ramani, S.M. Jaeggi, E.N. Daubert, M. Buschkuehl, Domain-specific and domain-general training to improve kindergarten children's mathematics, J. Numer. Cogn. 3 (2017) 468–495. https://doi.org/10.5964/jnc.v3i2.31.

[68] *P. Räsänen, J. Salminen, A.J. Wilson, P. Aunio, S. Dehaene, Computer-assisted intervention for children with low numeracy skills, Cogn. Dev. 24 (2009) 450–472. https://doi.org/10.1016/j.cogdev.2009.09.003.

[69] *D. Rosenfeld, X. Dominguez, C. Llorente, S. Pasnik, S. Moorthy, N. Hupert, S. Gerard, R. Vidiksis, A curriculum supplement that integrates transmedia to promote early math learning: A randomized controlled trial of a PBS KIDS intervention, Early Child. Res. Q. 49 (2019) 241–253. https://doi.org/10.1016/j.ecresq.2019.07.003.

[70] *J.B. Salminen, T.K. Koponen, M. Leskinen, A.M. Poikkeus, M.T. Aro, Individual variance in responsiveness to early computerized mathematics intervention, Learn. Individ. Differ. 43 (2015) 124–131. https://doi.org/10.1016/j.lindif.2015.09.002.

[71] *J. Salminen, T. Koponen, P. Räsänen, M. Aro, Preventive Support for Kindergarteners Most At-Risk for Mathematics Difficulties: Computer-Assisted Intervention, Math. Think. Learn. 17 (2015) 273–295. https://doi.org/10.1080/10986065.2015.1083837.

[72] *J. Schacter, B. Jo, Improving low-income preschoolers mathematics achievement with Math Shelf, a preschool tablet computer curriculum, Comput. Human Behav. 55 (2016) 223–229. https://doi.org/10.1016/j.chb.2015.09.013.

[73] *J. Schacter, B. Jo, Improving preschoolers’ mathematics achievement with tablets: a randomized controlled trial, Math. Educ. Res. J. 29 (2017) 313–327. https://doi.org/10.1007/s13394-017-0203-9.

[74] *J. Schacter, J. Shih, C.M. Allen, L. DeVaul, A.B. Adkins, T. Ito, B. Jo, Math Shelf: A Randomized Trial of a Prekindergarten Tablet Number Sense Curriculum, Early Educ. Dev. 27 (2016) 74–88. https://doi.org/10.1080/10409289.2015.1057462.

[75] *K. Schenke, E.J.K.H. Redman, G.K.W.K. Chung, S.M. Chang, T. Feng, C.B. Parks, J.D. Roberts, Does “Measure Up!” measure up? Evaluation of an iPad app to teach preschoolers measurement concepts, Comput. Educ. 146 (2020) 103749. https://doi.org/10.1016/j.compedu.2019.103749.

[76] *E.L. Schroeder, H.L. Kirkorian, When seeing is better than doing: Preschoolers’ transfer of STEM skills using touchscreen games, Front. Psychol. 7 (2016) 1–12. https://doi.org/10.3389/fpsyg.2016.01377.

[77] *O. Segal-Drori, L.B.H. Kalmanovich, A. Shamir, Electronic Book for Promoting Emergent Math: A Comparison Between Kindergarteners at Risk for Learning Disabilities and With Typical Development, J. Educ. Comput. Res. 57 (2019) 954–977. https://doi.org/10.1177/0735633118769459.

[78] *F. Sella, P. Tressoldi, D. Lucangeli, M. Zorzi, Training numerical skills with the adaptive videogame “The Number Race”: A randomized controlled trial on preschoolers, Trends Neurosci. Educ. 5 (2016) 20–29. https://doi.org/10.1016/j.tine.2016.02.002.

[79] *A. Shamir, D. Baruch, Educational e-books: A support for vocabulary and early math for children at risk for learning disabilities, EMI. Educ. Media Int. 49 (2012) 33–47. https://doi.org/10.1080/09523987.2012.662623.

[80] *A. Shamir, I. Lifshitz, E-Books for supporting the emergent literacy and emergent math of children at risk for learning disabilities: can metacognitive guidance make a difference?, Eur. J. Spec. Needs Educ. 28 (2013) 33–48. https://doi.org/10.1080/08856257.2012.742746.

[81] *J. Simarmata, T. Limbong, A.R.S. Tambunan, M.P. Simanjuntak, R. Limbong, A. Purnomo, R.D. Kumalasari, F. Anam, K. Khoifulloh, K. Nisa, Y. Aryni, O.N. Purba, F.A. Sianturi, P. Tarigan, E. Napitupulu, Multimedia of number recognition for early childhood using image object, Int. J. Eng. Technol. 7 (2018) 796–798. https://doi.org/10.14419/ijet.v7i3.2.18760.

[82] *S. Soydan, Analyzing efficiency of two different methods involving acquisition of operational skills by preschool children, Eurasia J. Math. Sci. Technol. Educ. 11 (2015) 129–138. https://doi.org/10.12973/eurasia.2014.1036a.

[83] *K.P. Thai, L. Ponciano, Improving outcomes for at-risk prekindergarten & kindergarten students with a digital learning resource, J. Appl. Res. Child. 7 (2016).

[84] *I. Weiss, B. Kramarski, S. Talis, Effects of multimedia environments on kindergarten children's mathematical achievements and style of learning, EMI. Educ. Media Int. 43 (2006) 3–17. https://doi.org/10.1080/09523980500490513.

[85] *A.J. Wilson, S. Dehaene, O. Dubois, M. Fayol, Effects of an adaptive game intervention on accessing number sense in low-socioeconomic-status kindergarten children, Mind, Brain, Educ. 3 (2009) 224–234. https://doi.org/10.1111/j.1751-228X.2009.01075.x.

[86] *N. Zaranis, The use of ICT in kindergarten for teaching addition based on realistic mathematics education, Educ. Inf. Technol. 21 (2016) 589–606. https://doi.org/10.1007/s10639-014-9342-8.

[87] *N. Zaranis, Does the use of Information and Communication Technology through the use of Realistic Mathematics Education help kindergarten students to enhance their effectiveness in addition and subtraction?, Presch. Prim. Educ. 5 (2017) 46-62. https://doi.org/10.12681/ppej.9058.

[88] *N. Zaranis, E. Synodi, A comparative study on the effectiveness of the computer assisted method and the interactionist approach to teaching geometry shapes to young children, Educ. Inf. Technol. 22 (2017) 1377–1393. https://doi.org/10.1007/s10639-016-9500-2.

[89] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, D. Altman, G. Antes, D. Atkins, V. Barbour, N. Barrowman, J.A. Berlin, J. Clark, M. Clarke, D. Cook, R. D'Amico, J.J. Deeks, P.J. Devereaux, K. Dickersin, M. Egger, E. Ernst, P.C. Gøtzsche, J. Grimshaw, G. Guyatt, J. Higgins, J.P.A. Ioannidis, J. Kleijnen, T. Lang, N. Magrini, D. McNamee, L. Moja, C. Mulrow, M. Napoli, A. Oxman, B. Pham, D. Rennie, M.

Sampson, K.F. Schulz, P.G. Shekelle, D. Tovey, P. Tugwell, Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement, PLoS Med. 6 (2009) e1000097. https://doi.org/10.1371/journal.pmed.1000097.

[90] J.P. Higgins, S. Green, Cochrane handbook for systematic reviews of interventions (vol. 5), Wiley Online Library, 2008.

[91] M.B. Miles, A.M. Huberman, Qualitative data analysis, second ed., Sage, 1994.

[92] J.A.C. Sterne, J. Savović, M.J. Page, R.G. Elbers, N.S. Blencowe, I. Boutron, C.J. Cates, H.Y. Cheng, M.S. Corbett, S.M. Eldridge, J.R. Emberson, M.A. Hernán, S. Hopewell, A. Hróbjartsson, D.R. Junqueira, P. Jüni, J.J. Kirkham, T. Lasserson, T. Li, A. McAleenan, B.C. Reeves, S. Shepperd, I. Shrier, L.A. Stewart, K. Tilling, I.R. White, P.F. Whiting, J.P.T. Higgins, RoB 2: A revised tool for assessing risk of bias in randomised trials, BMJ. 366 (2019) 1–8. https://doi.org/10.1136/bmj.l4898.

[93] C. Herodotou, Young children and tablets: A systematic review of effects on learning and development, J. Comput. Assist. Learn. 34 (2018) 1–9. https://doi.org/10.1111/jcal.12220.

[94] S.M. Ross, G.R. Morrison, D.L. Lowther, Using experimental methods in higher education research, J. Comput. High. Educ. 16 (2005) 39–64. https://doi.org/10.1007/BF02961474.

[95] L.B. Christensen, Experimental methodology, Allyn and Bacon, Boston, 1991.

[96] L. Verschaffel, F. Depaepe, Z. Mevarech, Learning Mathematics in Metacognitively Oriented ICT-Based Learning Environments: A Systematic Review of the Literature, Educ. Res. Int. 2019 (2019). https://doi.org/10.1155/2019/3402035.

[97] F. Paas, A. Renkl, J. Sweller, Cognitive load theory and instructional design: Recent developments, Educ. Psychol. 38 (2003) 1-4.

[98] M.C. Kim, M.J. Hanna, Computers & Education Scaffolding problem solving in technology-enhanced learning environments (TELEs): Bridging research and theory with practice, Comput. Educ. 56 (2011) 403–417. https://doi.org/10.1016/j.compedu.2010.08.024.

[99] A. Raes, T. Schellens, The effects of teacher-led class interventions during technology-enhanced science inquiry on students’ knowledge integration and basic need satisfaction, Comput. Educ. 92–93 (2016) 125–141. https://doi.org/10.1016/j.compedu.2015.10.014.

[100] A.C.K. Cheung, R.E. Slavin, How Methodological Features Affect Effect Sizes in Education, Educ. Res. 45 (2016) 283–292. https://doi.org/10.3102/0013189X16656615.

[101] A. All, E.P. Nuñez Castellar, J. Van Looy, Towards a conceptual framework for assessing the effectiveness of digital game-based learning, Comput. Educ. 88 (2015) 29–37. https://doi.org/10.1016/j.compedu.2015.04.012.

[102] S. Batchelor, J. Torbeyns, L. Verschaffel, Affect and mathematics in young children: an introduction, Educ. Stud. Math. 100 (2019) 201–209. https://doi.org/10.1007/s10649-018-9864-x.

[103] S. Vanbecelaere, K. Van den Berghe, F. Cornillie, D. Sasanguie, B. Reynvoet, F. Depaepe, The effectiveness of adaptive versus non-adaptive learning with digital educational games, J. Comput. Assist. Learn. 36 (2019) 502–513. https://doi.org/10.1111/jcal.12416.

[104] A. All, E.P. Nuñez Castellar, J. Van Looy, Assessing the effectiveness of digital game-based learning: Best practices, Comput. Educ. 92–93 (2016) 90–103. https://doi.org/10.1016/j.compedu.2015.10.007.