Computers & Education 157 (2020) 103953

Contents lists available at ScienceDirect

Computers & Education

journal homepage: http://www.elsevier.com/locate/compedu

Effectiveness of digital-based interventions for children with mathematical learning difficulties: A meta-analysis

Silvia Benavides-Varela [a,b,*], Claudio Zandonella Callegher [a], Barbara Fagiolini [c], Irene Leo [a], Gianmarco Altoè [a], Daniela Lucangeli [a]

[a] Department of Developmental Psychology and Socialization, University of Padova, Padova, Italy
[b] Department of General Psychology, University of Padova, Padova, Italy
[c] Department of Science and High Technology, University of Insubria, Varese, Italy

ARTICLE INFO

Keywords:
Dyscalculia
Mathematical disabilities
Mathematical difficulties
Digital-based tools
Media in education
Educational videogames
Intervention effects

ABSTRACT

The purpose of this work was to meta-analyze empirical evidence about the effectiveness of digital-based interventions for students with mathematical learning difficulties. Furthermore, we investigated whether the school level of the participants and the software instructional approach were decisive modulated factors. A systematic search of randomized controlled studies published between 2003 and 2019 was conducted. A total of 15 studies with 1073 participants met the study selection criterion. A random effects meta-analysis indicated that digital-based interventions generally improved mathematical performance (mean ES = 0.55), though there was a significant heterogeneity across studies. There was no evidence that videogames offer additional advantages with respect to digital-based drilling and tutoring approaches. Moreover, effect size was not moderated when interventions were delivered in primary school or in preschool.

1. Introduction

A developmental learning disorder can be a very serious handicap for a child, especially if the skills affected, like mathematical ones, are critical in modern societies (e.g. Duncan et al., 2007; Ritchie & Bates, 2013). Low numeracy affects various aspects of people's life. It negatively impacts school attainment, mental health and self-esteem in children (Fritz et al., 2019). Moreover in adulthood, it reduces the range of working opportunities (Rivera-Batiz, 1992) and it compromises an individual's independence in activities of the everyday life (Arcara et al., 2017; Benavides-Varela et al., 2015, 2017, 2020; Semenza et al., 2014).

The seriousness of the mathematical difficulties can vary considerably and so do the terminologies used across research studies, government reports, and authorities, when referring to gravity, causes, and developmental trajectories of the various levels of mathematical weaknesses (Mazzocco, 2005; Mazzocco & Räsänen, 2013; Butterworth, 2019). Thus, currently there is no clear, generally accepted classification of developmental mathematical difficulties, despite numerous attempts (e.g. Karagiannakis et al., 2014).

The Diagnostic and Statistical Manual of Mental Disorders (DSM), the reference document by the American Psychiatric Association, refers to dyscalculia (named Mathematical Learning Disability –MLD- in the fifth Edition of the manual - DSM 5), as a neuro-developmental disorder with specific learning impairment in mathematics. Children with dyscalculia have impairment in processing

* Corresponding author.University of Padova, Via Venezia 8, 35131, Padova, Italy.
E-mail address: silvia.benavidesvarela@unipd.it (S. Benavides-Varela).

https://doi.org/10.1016/j.compedu.2020.103953
Received 13 July 2019; Received in revised form 7 June 2020; Accepted 9 June 2020
Available online 30 June 2020

numerical information, learning arithmetic facts, and have poor calculation and math reasoning abilities. These impairments are below what would be expected for the individual's age, intelligence, and level of educational instruction, and occur in the absence of visual or hearing impairments, mental disorders (e.g. depression, anxiety, etc.), neurological disorders, psycho-social difficulty or language differences (American Psychiatric Association, 2013).

In line with this view, most authors reserve the term mathematical learning disability or dyscalculia to a "presumed biologically based set of math difficulties" (e.g. Mazzocco, 2005). Mathematical learning difficulties (MD), on the other hand, often refers to mathematical deficits in a broader sense (Karagiannakis et al., 2014), thus comprising dyscalculia, as well as deficits that can be caused by non-neurobiological factors (Mazzocco, 2005; Mazzocco & Räsänen, 2013). It is anticipated that, the target studies of this meta-analysis focused on students with specific difficulties in the domain of numbers (called "dyscalculics", "children with specific learning disabilities in mathematics", "low-performing in mathematics", "at risk for dyscalculia" in the original papers). However, because the criteria for diagnosing dyscalculia vary considerably across studies, the conservative term MD will be adopted hereinafter to refer to the target group.

MD can manifest at different points in a child's school career, not only in the learning of basic facts or in learning to apply previously acquired knowledge to solve numerical problems but also in the learning of preliminary mathematics skills such as counting, seriation (Van De Rijt & Van Luit, 1998), number sense, or subitizing, which can be traced before entering primary education.

This suggests that children with MD may struggle both with informal mathematics abilities (e.g. numbering, performing simple arithmetic problems using tokens or fingers) and formal school-taught abilities such as reading and writing Arabic numerals, and recalling memorized multiplication facts (Ginsburg & Baroody, 2003; Jordan et al., 2009).

There is also an open debate about developmental trajectories and reasons for a failure in learning mathematics. Some authors agree in that environmental, cultural, or economic disadvantaged situations increase the likelihood of experiencing poor mathematical outcomes throughout the educational path, particularly when a child has neurobiological dispositions to number deficits (Mazzocco & Räsänen, 2013). When such contextual factors are verified, children are considered "at risk" for manifesting mathematical difficulties.

MD can be often accompanied by psychological and behavioral problems, which might in turn intensify the negative academic outcomes. Students with MD report emotional distress and can develop low selfefficacy, lack of motivation, feelings of guilt, mathematics anxiety and even school phobia (e.g. Ashcraft & Ridley, 2005; Ramirez et al., 2018).

Fortunately, many efforts have been made in the last decades to support students in primary or secondary school (for recent reviews see Fritz et al., 2019; Chodura et al., 2015; Dowker, 2017; Jitendra et al., 2018), and in preschool for boosting children's first steps in mathematics learning (e.g Aunio, 2019; Bryant et al., 2011; Sella, Tressoldi, Lucangeli, & Zorzi, 2016; Outhwaite et al., 2019; Wilson et al., 2009). Moreover, recent advances in technology have further facilitated the advent of new digital-based interventions (Räsänen, Laurillard, Käser, & von Aster, 2019). However, from the great number of emerging apps, programs, websites, etc. that are available to train mathematical skills, only a small portion has been subjected to formal evaluation among children with MD (Drigas et al., 2016; Kroeger et al., 2012). The distinction between the results obtained in typically achieving children and children with MD is by no means trivial. Significant effects reported among typically performing children (e.g. Gouet et al., 2018; Li & Ma, 2010; López-Morteo & López, 2007; Rosas et al., 2003; Valle-Lisboa et al., 2016; Kulik, 1994), might not necessarily replicate among children that require specialized assistance. The successful implementation of new instruments among students who generally find learning especially challenging requires a careful integration of teaching strategies, research-based principles (Ginsburg et al., 2013), and specific design recommendations (Brunda & Bhavithra, 2010; Cezarotto & Battaiola, 2016) that could set the scene for the children's conceptual change and active engagement in the learning of math concepts (Seo & Woo, 2010). Providing sufficient number of practices and immediate ability/effort feedback, as well as individually adapting task difficulty based on either the child's cognitive profile or the progression within the game, appear among the instructional features that contribute to creating successful mathematical learning outcomes in digital-based interventions for students struggling with math (e.g. Cezarotto; Battaiola, 2016; Seo & Bryant, 2009). Design features recommendations also include reducing the amount of instructions, using visually attractive animations and graphics as well as graphic characters to increase the learning motivation. It is also recommended to locate the mechanics in a playful environment, to avoid using too many –potentially distracting– graphics unrelated to the instructional purposes, and to present simple and consistent interfaces acting as a background for the game activities (e.g. Cezarotto; Battaiola, 2016; Seo & Woo, 2010). Highly innovative intervention programs as well as adaptive computer videogames based on neuroscience research have been recently developed for the remediation of dyscalculia (e.g. Butterworth et al., 2011; Kucian et al., 2011; Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009; Wilson et al., 2006). These specialized digital-based interventions might offer distinctive benefits for learners, teachers and researchers. They can contribute to reducing training time and instructor load (Mitchell & Savill-Smith, 2004) and at the same time enable individualized attention to the learner (Butterworth & Laurillard, 2010). From the point of view of the student, they constitute alternative ways of studying (Durkin et al., 2015; Gee, 2003) and facilitate the link to abstract concepts in ways that are not generally possible using paper and pencil, e.g. "zooming into a 1–10 number line to discover decimal numbers" (Butterworth & Laurillard, 2010, p. 531). Furthermore, virtual environments enable a private feedback that can be extremely valuable for learners who struggle to carry on, and repeatedly suffer defeats in normal classroom contexts (Butterworth & Laurillard, 2010). In that sense, digital-based interventions could be particularly useful for improving the students' self-esteem and their motivation (Dempsey et al., 1994; Ritchie & Dodge, 1992). Despite the proposed advantages of incorporating digital tools in mathematics interventions, currently researchers have found mixed results regarding their effects.

1.1. Review of the previous summative studies into digital-based mathematics interventions

Numerous meta-analytic studies have been published generally reporting the outcomes of digital-based mathematics interventions for typically achieving learners (e.g. Li & Ma, 2010; Kulik, 1994). Some studies have reported the effects on students with learning disabilities (Jitendra et al., 2018; Kroesbergen & Van Luit, 2003; Li & Ma, 2010; Seo & Bryant, 2009) mental retardation (Kroesbergen & Van Luit, 2003; Mastropieri et al., 1991; Miller et al., 1998), and MD (Chodura et al., 2015; Kroesbergen & Van Luit, 2003). Their findings provide mixed conclusions regarding the effectiveness of digital tools in mathematics education. In some of the studies, the authors concluded that digital-based tools were less effective than a teacher in assisting students with special needs (e.g. Kroesbergen & Van Luit, 2003), or that they did not provide systematic effective changes to the learning process (e.g Mastropieri et al., 1991; Seo & Bryant, 2009; Kulik, 1994). On the other hand, Li and Ma (2010) found statistically significant positive effects of computer-technologies on mathematics achievement and larger effects on interventions for children with special needs compared to the effects on general education students. Similarly, Jitendra and colleagues also carried out a meta-analysis including interventions for students with mathematical difficulties and learning difficulties in secondary school (Jitendra et al., 2018). This study reported that digital-based modules were more effective as compared with regular classroom instruction, but did not provide an additional advantage as compared to other instructional approaches (e.g. non-computerized visual modules). Noticeably, all these findings emerged from evaluations of special needs students presenting highly heterogeneous difficulties, including for instance students with low-IQ, various types of learning, physical, and emotional disabilities, ADHD, blind, etc., in addition to those with specific mathematical difficulties. However, children with learning disabilities in general and with mathematical difficulties in particular, might show different learning profiles. As mentioned above, developmental dyscalculia -one of the core school academic disabilities-may develop in children with normal IQ and in the absence of difficulties in other domains, skills or abilities (Butterworth, 2019). Focusing on interventions targeting children with specific difficulties in the domain of numbers may thus provide some important insights for effective interventions to these children.

To our knowledge only one summative study has focused on this specific group. The study by Chodura et al. (2015) meta-analyzed 35 studies with the aim of evaluating the effectiveness of various types of interventions specifically designed for children with MD. The study found an overall positive effect of specialized interventions, but reported no significant differences between digital-based and face-to-face interventions. However, like previous studies, the study of Chodura and colleagues focused on interventions carried out from elementary school, which could not be generalized to the growing body of literature that evaluates early interventions for severely at risk children, before they enter elementary school. Moreover, because the study evaluated various types of interventions (not only digital-based ones), it did not investigate software characteristics thoroughly. For instance, one important distinction, which could influence the effectiveness of a digital-based intervention, is the software instructional approach: whether it is founded on adaptive and interactive videogames or on tutoring and drilling strategies.

1.2. Theoretical background and purpose of this study

While investigating the overall effectiveness and the parameters that may characterize successful interventions to help children's mathematical performance, the review research described above has some limitations. First, the summative studies have provided inconsistent conclusions concerning the effectiveness of incorporating digital tools in mathematics interventions and most of the reviews included primary investigations with students showing a wide range of special needs. This makes it difficult to evaluate the interventions among children with specific deficits in mathematics. Second, most of the previous research has focused on children from elementary school (e.g. Chodura et al., 2015; Kroesbergen & Van Luit, 2003; Seo & Bryant, 2009) and secondary school (Jitendra et al., 2018). However, new theoretical and practical developments have pointed out the importance of early interventions that target children already in preschool (e.g. Aunio, 2019; Benavides-Varela et al., 2016; Bryant et al., 2011; Sella et al., 2016; Outhwaite et al., 2019), calling for a systematic integration of the literature including also the studies carried out in these early stages. Third, research results are beginning to provide further insights into the benefits of incorporating video and interactive games to support math learning. To date, however, no study has directly assessed whether videogame interventions moderate the general effects obtained on specialized interventions. In the context of this background, the primary goal of this study was to systematically review and meta-analyze peer-reviewed randomized controlled trials that focused on children with MD. Specifically, the present review sought to answer the following questions:

1. Do digital-based interventions significantly impact mathematics achievement of all the students with mathematical learning difficulties? For the purpose of this review, digital-based interventions refer to those in which students are engaged one-on-one with a software, App, or digital environment available on personal computers, tablets, or smartphones and that had been specifically designed to provide supplementary math learning opportunities.
2. Do the effects vary by the school level in which the intervention is carried out (pre-school/elementary/high school)?
3. Does the software instructional approach (videogames vs. digital-based tutorials/drilling) moderate the intervention outcomes? Here we refer to videogames as digital-based tools that propose ludic activities and that require the student to indirectly apply numerical concepts or carry out numerical computations to win or to proceed to the next level of the game (Stultz, 2013). Digital-based tutorials/drilling refer to software that explicitly instruct mathematical concepts and repeatedly present audio-visual information/exercises on a given topic (usually associated with the students' specific weaknesses).

The results of this analysis should bring new insights for future pedagogical and educational decisions. In particular, they may provide summative information to assist teachers, parents, and other tutors when choosing appropriate instruments to support children struggling in mathematics.

2. Methods

The literature search used the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) methodology (Moher et al., 2009). The PRISMA consists of a 27-item checklist and a four-phase (Identification, Screening, Eligibility, and Inclusion) flow diagram to facilitate the preparation and reporting of a robust protocol, and for a critical appraisal of systematic-reviews (Moher et al., 2009). PRISMA has been implemented in previous studies to guarantee comprehensive and objective reporting of meta-results (e.g. Stanmore et al., 2017).

2.1. Literature search and inclusion criteria

A literature search was conducted until March 2019 by means of PsycINFO, Google Scholar, and Educational Resources Information Center (ERIC) databases. The search was restricted to the period from 2003 to 2019 since the majority of systematic and meta-analytic reviews focusing on digital-based interventions for children with learning difficulties had already included studies published between 1980 and 2002 (e.g. Kroesbergen & Van Luit, 2003; Kulik, 1994; Li & Ma, 2010; Seo & Bryant, 2009; Woodward & Carnine, 1993). Eligible studies were group-designed randomized controlled trials which compared the effects of digital-based interventions to control conditions and which provided some statistical elements to support inferences at the population level. Single case interventions, observational reports, conference papers, dissertations, research foundation papers that are limited to describing software details and program development, intervention studies using tools that have not been directly evaluated in children with mathematical learning disabilities, and newsletter articles were not included in this review. Studies needed to report students' performance in any domain of mathematics as their dependent variable. Additionally, the studies needed to include statistical information (Sample Size, Mean, Standard Deviation) for their effect size calculation. Where only part of these data were reported, the corresponding authors of the respective articles were contacted to request the missing information. Studies could have been conducted in any country, but only English-language articles published in peer-reviewed journals were included. The reference sections of the eligible articles and previous reviews or book chapters were also scanned to locate other possible studies on this topic that could meet the initial criteria.

The terms used to locate potentially relevant studies were the following: mathematics; dyscalculia; videogames; interventions; computer-assisted instruction; educational technology; mathematical learning; mathematics teaching; number sense; mathematics achievement; mathematical difficulties; randomized; controlled; control group; control condition.

2.2. Coding procedure

Articles were screened for eligibility by three independent authors (SBV, BF and CZC). Disagreements were resolved through pairwise discussions until consensus was reached. A systematic coding form was used by SBV and BF to record relevant information from each study. The studies were coded taking into account the following characteristics:

(i) Primary outcome – Mathematical performance: This was defined as the change in any ability to solve a problem in any domain of mathematics following a digital-tool intervention (or control condition). Sample sizes, means and standard deviations were extracted for the effect size calculation.

(ii) Potential moderators: Data on factors that may influence the effect size of the interventions were also extracted from each article. In agreement with the aims of the present study, a categorical distinction was made while coding the type of program (i.e. tutorial and drill & practice vs videogames), and school level (high school/primary school/preschool). Other specific characteristics of the intervention (length in weeks, number of sessions per week, session duration and total number of sessions during intervention), and topic (math facts fluency, fractions, subtractions, additions, etc.) were also extracted but not included in the moderator analysis due to high variability in the levels of each factor.

2.3. Statistical analysis

The preliminary dataset included 15 studies. We summarized studies' results considering effect size and variance based on the d_{ppc2} index suggested by Morris (2008). In the case of studies with repeated measures in both treatment and control groups (pretest--posttest-control design; PPC), d_{ppc2} allows to quantify the treatment effect size as the difference between mean pre-post change in the treatment group and the mean pre-post change in the control group, divided by the pooled pre-test standard deviation:

$$d_{ppc2} = c_p \frac{(M_{post,T} - M_{pre,T}) - (M_{post,C} - M_{pre,C})}{SD_{pooled,pre}}, \qquad (1)$$

where $M_{pre,T}$, $M_{post,T}$ and $M_{pre,C}$, $M_{post,C}$ are respectively the pre, post mean scores of the treatment group and the pre, post mean scores of the control group. $SD_{pooled,pre}$ is the pooled pre-test standard deviation, computed considering only the pre-test standard deviation of the two groups, and c_p is a bias adjustment for small sample size.

Compared to other indexes, d_{ppc2} offers better results in terms of bias, precision, and robustness to heterogeneity of variance (Morris, 2008). The d_{ppc2} values were interpreted according to the criteria suggested by Cohen (1988): small effects from 0.2 to 0.5; medium effects from 0.5 to 0.8; large effects greater than 0.8. A complete description of the index is reported in the supplemental material.

When studies included multiple treatment groups or control groups (such as the case of Aunio & Mononen, 2018; Hassler Hallstedt et al., 2018; Nelson et al., 2013), we selected the passive control group and the computer-based treatment group to obtain a better evaluation of the treatment effect. Whereas, if treatment groups were considered equivalent from a research point of view (such as the case of Baroody et al., 2013) they were merged together to yield a combined mean and standard deviation (see chapter 25 Borenstein et al., 2009 for technical details). We noticed that Kucian et al. (2011) and Räsänen et al., 2009 included as control groups only children with age-appropriate calculation performance (not children with mathematical difficulties). This does not allow to obtain a meaningful interpretation of the d_{ppc2} index. Thus, the two studies were excluded from the meta-analysis and their results were discussed separately. The final dataset included 13 studies. Full description of the preparation of the dataset is reported in the supplemental material.

The d_{ppc2} estimated mean and variance was calculated using raw mean scores, standard deviation, and sample size of the treatment and control groups reported in the studies. In order to compute d_{ppc2} variance, the correlation between pre- and post-test scores is needed. However, only Salminen et al. (2015) reported this correlation, with $r_{pre-post}$ ranging from 0.72 to 0.90. Thus, $r_{pre-post} = 0.70$ was used as reference value for all the studies and meta-analysis results were evaluated in a sensitivity analysis using $r_{pre-post} = 0.50$, which gives greater variance (i.e., more conservative results), and $r_{pre-post} = 0.90$, which gives smaller variance (i.e., less conservative results). Where studies reported more than a task, effect size and variance were firstly computed for each task separately and then combined into composite summary effect and variance, following recommendations to take into account dependence of the information (see chapters 23 and 24 in Borenstein et al., 2009). Different formula were applied if the multiple task were completed by the same subjects (such as the case of Baroody et al., 2012, 2013; Hassler Hallstedt et al., 2018; Käser et al., 2013; Salminen et al., 2015) or if they were completed by different subjects (such as the case of Burns et al., 2012). In particular, to compute the composite summary variance, the correlation between the different tasks completed by the same subjects is needed. However, no study reported this correlation. Thus, $r_{tasks} = 0.50$ was used as reference value in all cases and meta-analysis results were evaluated in a sensitivity analysis using $r_{tasks} = 0.30$, which gives smaller variance (i.e., less conservative results), and $r_{tasks} = 0.70$, which gives greater variance (i.e., more conservative results).

The analysis were conducted with R software (R Core Team, 2019). Firstly we ran a random-effects model meta-analysis using the restricted maximum likelihood method with the R package *Metafor* (Viechtbauer, 2010). Next, we explored the heterogeneity between studies through inspection of forest plot and evaluation of the Q-statistic (Hedges & Olkin, 2014). Q-statistic is distributed like the chi-square under the null hypothesis, with a significant chi value indicating the presence of heterogeneity across studies. Moreover, to estimate the magnitude of the heterogeneity we considered the I^2 index (i.e., the proportion of observed variance that reflects real and not random difference between studies effect sizes; Borenstein et al., 2009). High values of I^2 suggest that difference between results are related to real differences across studies (i.e., different constructs or different study design). On the contrary, low values of I^2

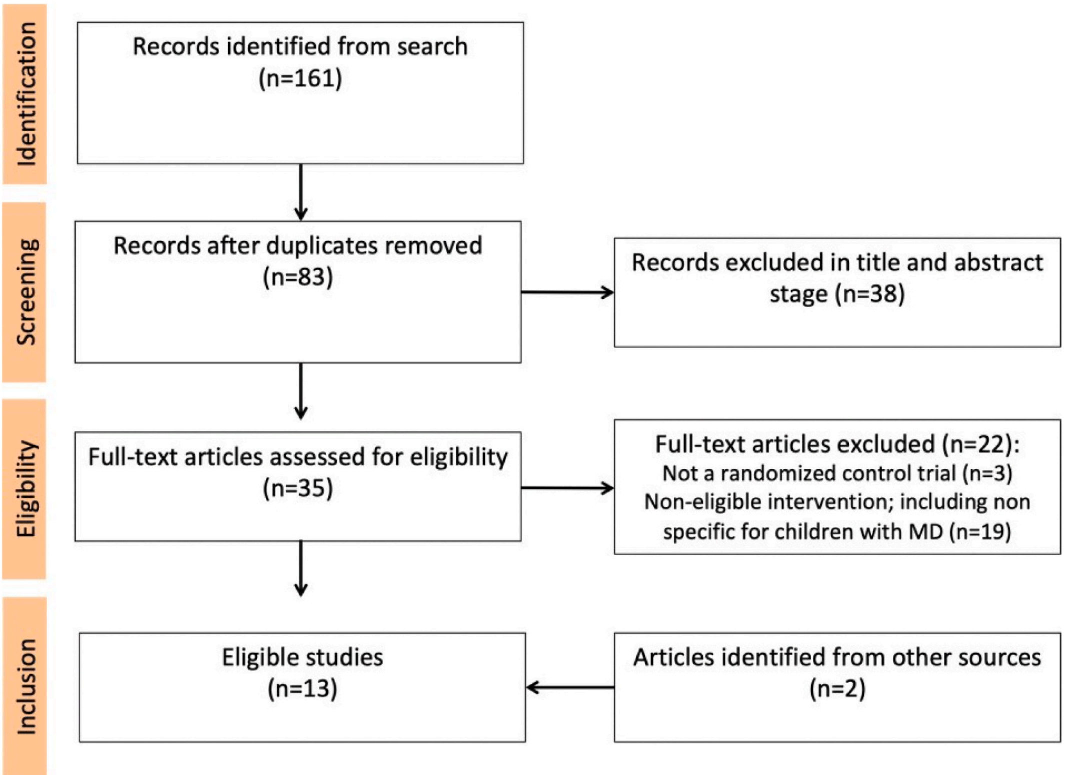

Fig. 1. PRISMA flow diagram of systematic search and study selection.

Table 1
Descriptive statistics of the studies included in the review.

Study				Participants		Treatment Group		Control Group		$^{d}ppc2$	
Authors	Year	Country	*N*	Males/Females	School level	Intervention	$^{n}treatment$	Control	$^{n}control$	Effect size	Variance
Aunio & Mononen	2018	Finland	14	5/9	Preschool	Video-Game	7	Passive	7	−0.48	0.18
Baroody et al.	2012	United States	28	12/16	Preschool	Tutorial-Practice	15	Active Math	13	1.55	0.08
Baroody et al.	2013	United States	64	23/41	Primary School	Tutorial-Practice	43	Active Math	21	0.97	0.04
Burns et al.	2012	United States	442	NA	Primary School	Tutorial-Practice	216	Active Math	226	0.61	0.01
Castro et al.	2014	Brazil	26	16/10	Primary School	Video-Game	13	Active Math	13	0.96	0.11
Fuchs et al.	2006	United States	33	21/12	Primary School	Tutorial-Practice	16	Active Spelling	17	1.01	0.09
Hassler Hallstedt et al.	2018	Sweden	127	66/61	Primary School	Video-Game	75	Passive	52	0.54	0.01
Käser et al.	2013	Switzerland	41	14/27	Primary School	Video-Game	20	Passive	21	0.69	0.04
Kucian et al.	2011	Switzerland	32	13/19	Primary School	Video-Game	16	Active Normative	16	0.31	0.08
Leh & Jitendra	2013	United States	25	12/13	Primary School	Tutorial-Practice	13	Active Math	12	−0.79	0.11
Mohd Syah et al.	2016	Malasya	50	NA	Primary School	Video-Game	25	Passive	25	1.05	0.06
Nelson et al.	2013	United States	53	NA	Primary School	Tutorial-Practice	26	Passive	27	0.65	0.05
Räsänen et al.	2009	Finland	59	32/27	Preschool	Video-Game	30	Passive Normative	29	0.41	0.04
Salminen et al.	2015	Finland	21	9/12	Preschool	Video-Game	13	Passive	8	0.54	0.10
Stultz	2013	United States	58	36/22	High School	Tutorial-Practice	29	Active Math	29	−0.46	0.04

Note: Total sample: 1073. NA: not available.

Table 2
Characteristics of the intervention for each study included in the review.

Study	Intervention Characteristics				
Authors	Year	Description	Total number of digital-based of each sessions	Duration session	Measured outcome
Aunio & Mononen	2018	Multiple number early skills using "Lola's world"	15 sessions over 3 weeks	15 min	Total ENT evaluation Experimental Vs Active Control
Baroody et al.	2012	Structured add-0/1 rules	18 sessions over 9 weeks	30 min	Mental addition fluency. Pooled ES including practiced and unpracticed (transfer) items
Baroody et al.	2013	add-1 rule and near-doubles reasoning strategy	20 sessions over 10 weeks	30 min	Mental addition fluency structured add-1 rule.Pooled ES including practiced and unpracticed (transfer) items
Burns et al.	2012	Fact retrieval using "Math Facts"	24 to 45 sessions over 8–15 weeks	10–15 min	Pooled ES including 3rd and 4th grades
Castro et al.	2014	Multiple numerical skills using "Tom's Rescue"	10 sessions over 5 weeks	60 min	Mental math problems and written arithmetic operations using the Scholastic performance test of arithmetic
Fuchs et al.	2006	Fact retrieval using "Flash"	50 sessions over 18 weeks	10 min	Addition fact retrieval
Hassler Hallstedt et al.	2018	Basic arithmetic (addition and subtraction facts up to 12), number knowledge and word problems using"Chasing Planets"	56 sessions over 20 weeks	20 min	Addition and subtraction facts
Käser et al.	2013	Multiple numerical skills using "Calcularis"	60 sessions over 12 weeks	20 min line-10 tests	Pooled ES including Subtraction and Number
Kucian et al.	2011	Multiple numerical skills using "Rescue Calcularis"	25 sessions over weeks	5 15 min	Accuracy of math problems (addition and subtraction)
Leh & Jitendra	2013	Problem solving skills	15 sessions over 6 50 min weeks	Word problem solving	
Mohd Syah et al.	2016	Number orientation and arithmetic sign identification	5 sessions within a week	60 min Subtraction	Pooled ES including Counting, Addition and
Nelson et al.	2013	Fact retrieval using "Math Facts"	4 sessions within 15–20 min a week	Digits correct per minute	
Räsänen et al.	2009	Approximate and exact number comparison using"Number Race" and "Graphogame-Math"	15 sessions over 3 10–15 min weeks	Number comparison. Pooled ES including Number Race and Graphogame-Math	
Salminen et al.	2015	Multiple numerical skills using "Graphogame-Math"	12-15 sessions 10–15 min over 3 weeks	Pooled ES including Enumeration, Verbal counting, Number Sets, Basic Addition	
Stultz	2013	Multiplication and division using "BMCSB" for fractions	10 sessions 90 min		Multiplying and dividing fractions

suggest that results across studies are similar and possible difference are related to random sampling.

2.3.1. Sensitivity analysis and evaluation of publication bias

To investigate robustness of the results, we ran two sensitivity analyses. First, we used the *leave-one-out* method to evaluate how results would change if studies were excluded one at time from the analysis. Substantial changes when a single study is removed are interpreted as lack of homogeneity and unreliable results (Viechtbauer & Cheung, 2010). Secondly, we evaluated results when different values are used for $r_{pre-post}$ and r_{tasks} coefficients. Moreover, publication bias was assessed using the funnel plot with the *trim and fill* method (Duval & Tweedie, 2000; Rothstein et al., 2005).

2.3.2. Effects of possible moderators

The role of possible moderators was examined using mixed-effects meta-regression models, the moderators were included as a fixed effects and were tested using Wald's chi-square (Viechtbauer, 2010). Considering the reduced number of studies and the unequal distribution among the different levels of the moderators, we conducted separately two analyses to evaluate the role of (1) software instructional approach, (2) school level. Results should be interpreted with caution as it was not possible to evaluate all the moderators at the same time.

3. Results

3.1. Search results

The search returned 161 results, reduced to 83 after duplicates were removed. Thirty-eight articles were further excluded after reviewing the titles and abstracts for eligibility. Full versions were retrieved for 35 articles, of which 13 articles were eligible for inclusion. Two additional eligible articles were identified from the reference lists of the full-texts. Thus, a total of 15 unique studies with independent samples were included in this review. The article screening process is detailed in Fig. 1.

3.2. Included studies, participant details and descriptive statistics

Descriptive statistics are reported in Table 1. Included studies were published between 2006 and 2018, most of them (10 out of 15) after 2012. Seven studies were conducted in the United States, three in Finland, two in Switzerland, and one each in Brazil, Sweden and Malaysia. Eligible outcome data was available from a total of 1073 participants across the 15 studies; 557 were assigned to the experimental intervention, 516 to control conditions. The sampled varied in size between 14 and 442 with most of the studies having

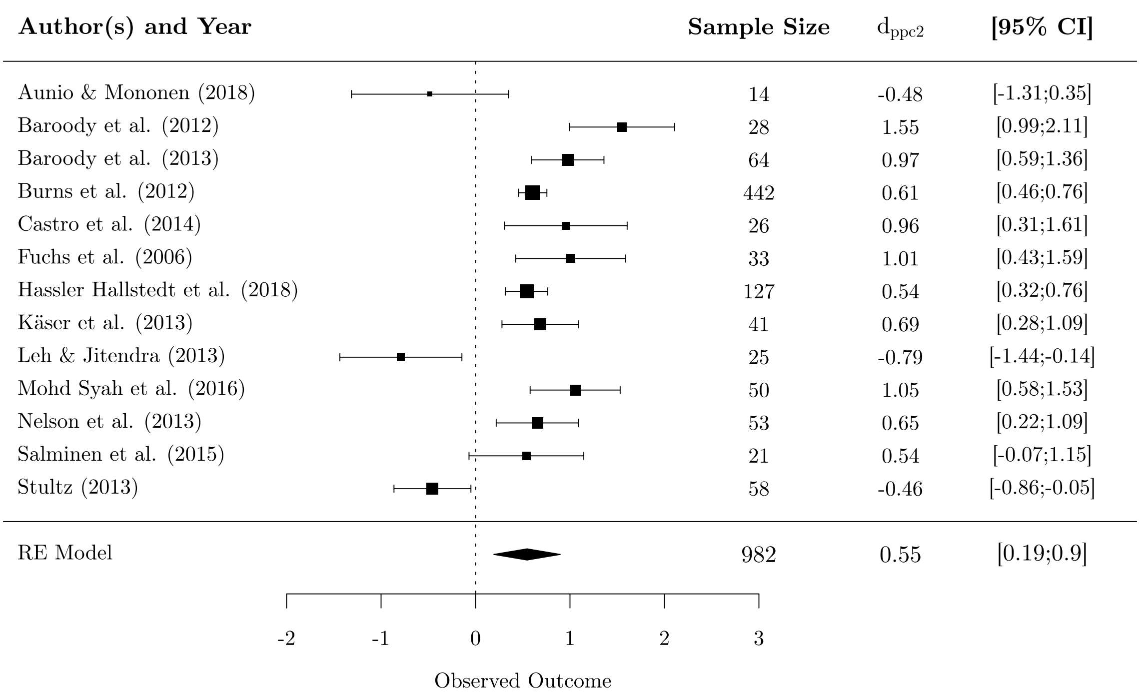

Fig. 2. Forest plot. Each square represents the effect size of the study together with 95% confidence interval. The size of the symbol is proportional to the study's weight.

less than 64 subjects. The mean age of the reported sample was 7.6 years (range = 5.6–16.3 years) and 55.0% of the participants were male. The majority of studies were conducted with children enrolled in primary school (N = 10). Four studies were conducted with pre-school children, and one in high school. Looking at the control group, six studies included a passive control group, six studies included an active control group trained in mathematics, and only one study included an active control group trained in a different topic (i.e. spelling). One study compared the results of the children with difficulties in mathematics against an active normative group (typically achieving children), and one study compared it against a passive normative group. As stated in the methods section, the last two studies were excluded from the meta-analysis.

Interventions lasted on average 7.8 weeks (range = 1–20 weeks), with an average of 3.4 sessions per week, ranging from 10 to 90 min per session. Software packages were designed to tackle a variety of numerical difficulties including fact retrieval (N = 3), reasoning strategy on calculation (N = 2), problem solving skills (N = 1), fractions (N = 1), approximate and exact number comparison (N = 1), number orientation and arithmetic sign identification (N = 1), or multiple numerical skills at the time (N = 6). N = 7 software packages used tutorials or drill & practice approaches, N = 8 used interactive videogames. Study details and intervention summaries are displayed in Table 2.

3.3. Random-effects model meta-analysis

3.3.1. Overall effects

The random effects meta-analysis showed a medium mean effect size, $d_{ppc2} = 0.55$, 95%CI (0.19 − 0.90), $p = 0.002$, meaning that children in the treatment groups showed a greater improvement in mathematical ability than children in the control groups (Fig. 2). It should be noted that despite the estimated effect size could be considered medium, the large confidence interval suggests that also small and large effect sizes could be considered consistent with the data.

3.4. Evaluating sensitivity of the analysis

The sensitivity analysis showed robustness of the results. The effect size did not vary considerably neither when results were computed excluding one study at time (i.e., *leave-one-out* method), nor when different values for $r_{pre-post}$ and r_{tasks} were used. In particular, the d_{ppc2} value varied between 0.47 and 0.65 ($mean = 0.55$, $SD = 0.05$) in the first case, and between 0.53 and 0.56 ($mean = 0.54$, $SD = 0.01$) in the second case (see Tables 3 and 4). Thus, the effect size remained consistently between medium values. However, also heterogeneity was consistently high (I^2 ranging from 81.56% to 96.96%).

3.4.1. Evaluating publication bias

The funnel plot with the *trim and fill* method added no hypothetical missing study (Fig. 3). Therefore, there was no evidence for publication bias. The included studies allow a representative analysis of the research questions.

3.4.2. Evaluating moderators

The tests of moderators were not significant: (1) software instructional approach $\chi^2(1) = 0.03$, $p = 0.86$, and (2) school level $\chi^2(1) = 0.006$, $p = 0.94$. In particular, to test the influence of school level we excluded the variable levels for which only one single study was available. Thus, high school students were not considered when testing age influence. This allowed to avoid unreliable results, as possible differences could be related to other study characteristics not considered. The full procedure is reported in the supplemental material.

Table 3
Sensitivity analysis using the Leave-One-Out Method.

Author(s) and Year	d_{ppc2}	95% CI	I^2
Aunio and Mononen (2018)	0.61	[0.26; 0.96]	90.15
Baroody et al. (2012)	0.47	[0.13; 0.81]	89.25
Baroody et al. (2013)	0.51	[0.13; 0.88]	90.96
Burns et al. (2012)	0.54	[0.15; 0.93]	88.38
de Castro et al. (2014)	0.51	[0.14; 0.89]	91.50
Fuchs et al. (2006)	0.51	[0.13; 0.88]	91.35
Hassler Hallstedt et al. (2018)	0.54	[0.15; 0.93]	89.89
Käser et al. (2013)	0.53	[0.15; 0.92]	91.44
Leh and Jitendra (2013)	0.65	[0.34; 0.95]	86.94
Mohd Syah et al. (2016)	0.50	[0.13; 0.88]	91.06
Nelson et al. (2013)	0.53	[0.15; 0.92]	91.53
Salminen et al. (2015)	0.54	[0.16; 0.93]	91.76
Stultz (2013)	0.64	[0.32; 0.96]	87.55
Mean	**0.55**		**90.14**

Note: Each line represents the results obtained excluding that study.

Table 4
Sensitivity analysis varying r_{tasks} and $r_{pre-post}$.

		r_{tasks}		
		.3	.5	.7
$r_{pre-post}$	.5	0.56 [0.23; 0.90] ($I^2 = 84.80$)	0.56 [0.22; 0.90] ($I^2 = 83.01$)	0.55 [0.21; 0.89] ($I^2 = 81.56$)
	.7	0.55 [0.20; 0.90] ($I^2 = 91.51$)	0.55 [0.19; 0.90] ($I^2 = 90.51$)	0.54 [0.19; 0.89] ($I^2 = 89.68$)
	.9	0.53 [0.17; 0.90] ($I^2 = 96.96$)	0.53 [0.16; 0.90] ($I^2 = 96.60$)	0.53 [0.16; 0.89] ($I^2 = 96.30$)

Note: d_{ppc2} [95%CI] and (I^2) are reported in each cell for given values of $r_{pre-post}$ and r_{tasks}. Total sample: $n = 982$.

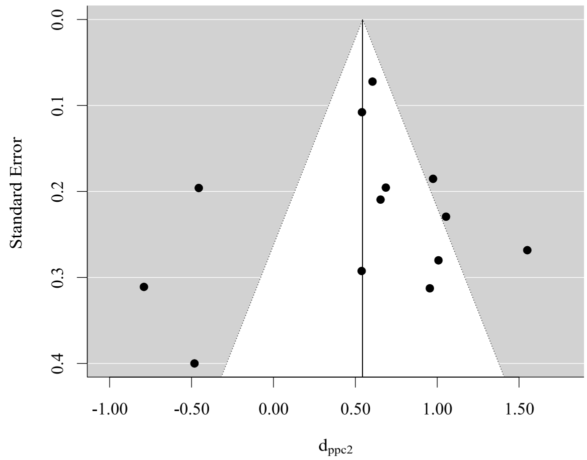

Fig. 3. Funnel plot. Each black dot represents one study included in the meta-analysis.

4. Discussion

Several successful or promising educational technology applications have been developed in the last decades for mathematics intervention programs. To date, a few programs have been developed specifically for remediation purposes in individuals with MD, and even less have been subjected to evaluations in randomized control trials. Thus, understanding to what extent digital tools can be useful for students suffering MD, compared to other tools and methods, is a relevant question particularly for teachers, parents, psychologists and other practitioners interested in implementing such tools.

The results of our work evidence a moderate but significantly positive effect of digital-based interventions on mathematics achievement (mean ES = +0.55). This finding partially confirms and extends the existing literature in various ways. First, it suggests that digital-based interventions subjected to formal evaluation among children with MD, compared to control conditions (e.g. face-to-face teaching, paper and pencil exercises, no intervention, interventions with non-specialized computer programs, etc.) resulted in higher mathematics achievement. This finding is in line with the positive results reported by Li and Ma (2010) when evaluating the effects of computer technologies among children with special needs compared to general education students. Moreover, the present study indicates that positive effects can be also observed in trials in which all participants have similar academic abilities (i.e. children struggling in maths both in the experimental and control conditions), as opposed to comparing the effects of the interventions in children with difficulties and typically achieving children of the same age, as Li & Ma did. Thus, not only students with MD improve more than typically achieving children following digital-based interventions, but also they seem to gain more from these interventions than children with similar difficulties following other control interventions.

Previous reviews and meta-analyses evaluating various types of mathematical interventions reported no additional benefits (e.g Kulik, 1994; Mastropieri et al., 1991; Seo & Bryant, 2009) or no significant differences between interventions with and without digital tools (e.g Chodura et al., 2015). Moreover, one study found that computer-assisted instruction was less effective than teacher instruction for students with special needs (e.g Kroesbergen & Van Luit, 2003). These conclusions appear in disagreement with our findings. However, we note that in their evaluation these works pooled children with different special needs and learning disabilities. Our work, instead, focused solely on interventions specific for helping children with MD. It is possible that students with such a specific cognitive profile might obtain additional benefits from the technological tools. Thus, eventual inconsistencies between previous findings and ours might be partly ascribable to the learning profiles of the participants included in the studies. In addition, it should be considered that, besides group composition, our meta-analysis differs from previous ones in the time point in which the analysis was carried out. Primary studies included in the most recently published reviews and meta-analysis (e.g Chodura et al., 2015; Kroesbergen & Van Luit, 2003; Li & Ma, 2010) were carried out 5 to19 years before the present work. Continuing interest in digital-based interventions for children with mathematical difficulties is however evidenced in our review. Indeed, 10 out 15 studies identified were carried out in the last 5 years and were thus out of the scope of previous studies. The new data that have become available since the previous reviews might have thus influenced the final outcomes in the summative evaluations.

Two factors were quantitatively assessed in the moderator analysis. The first one, school age, included interventions carried out on children from primary and preschool ages. Previous meta-analyses on mathematics evaluating digital-based interventions for improving mathematics included studies that were primarily conducted for students at the elementary (e.g Seo & Bryant, 2009) or secondary level (e.g Jitendra et al., 2018). There is no doubt that improving mathematics skills is important for these students. However, developing fundamental and basic conceptual understandings of mathematics is also crucial in the earliest phases of education. The recent advent of interventions in preschool ages -which had not been previously included in summative reports- respond to the growing need of assisting children when the first signs of mathematical difficulties emerge and also at a time in development when there are presumably greater chances for a substantial improvement. Studies indicate that children who enter kindergarten with low performance in numeracy skills continue to lag behind their peers in future school years and highlight the need of early interventions for low-performing children who are at risk for mathematical learning difficulties later at school (e.g. Duncan et al., 2007; Geary, 2011; Geary et al., 2012). In light of the new data available, one important question is whether digital-based interventions for kindergarteners yield better results than interventions carried out for older children with MD. Contrary to our initial expectations, the findings of the present study suggest that school level has no significant moderating effects. Thus, digital-based interventions provide promising results for both young and older children. However, the current results were obtained with relatively few studies per school level. More primary studies are thus needed to definitely conclude on the effectiveness of digital-interventions for children who struggle with mathematics understanding and who receive assistance at different points in development.

Another factor that was considered in the moderator assessment of the present study relates to the characteristics of the educational software. In particular, a comparison between the outcomes obtained with videogame programs and digital-based tutorials or drilling approaches was made. Research results are beginning to provide insights into the benefits of incorporating video games to support math interventions among children with MD. Videogames incorporate various modern features such as high-resolution graphics, sound effects, changing backgrounds or settings to teach the material to the students (Stultz, 2013). They seek to link entertainment with educational goals, to stimulate the children's desire to win and, in turn, to encourage their interest in mastering specific mathematical skills through different strategies. Moreover videogames, unlike the digital-based tutorial and drilling tools, often proposed comprehensive interventions that trained various math skills and computations rather than focusing on a single skill at the time. This is considered a successful feature to help low achievers who often necessitate a full range of support not only to attenuate noticeable difficulties, but also to support fundamental weaknesses that might go unnoticed. Additionally, training basic tasks along with more complex ones could be particularly useful for supporting those learners who generally lack confidence, as it is often the case among dyscalculic children. The results of our study, however, showed no modulation of the outcome associated with the instructional approach of the software. In other words, similar effects were obtained with digital-based tools using tutoring and drilling approaches and with videogame implementations.

5. Conclusions

Altogether the findings indicate that digital-based interventions positively impact mathematics achievement of students with MD. Digital-based interventions can be thus conceived as a proper instrument to assist children with specific mathematical needs and to offer them additional opportunities to carry out mathematical tasks in an alternative technological context. Moreover, according to our data, digital tools improve numerical performance and numerical understanding to a similar extent in MD children from primary school and in children from preschool ages. In other words, school level does not moderate the effects of the digital-based interventions. Finally, we found no evidence that digital-based interventions implementing a ludic approach (videogames) offer additional advantages for children with specific mathematics deficits with respect to digital-based interventions implementing drilling and tutoring approaches. However, digital-learning materials will surely continue to expand in the forthcoming years, particularly with increased access and usability of new technologies by parents, children and adolescents. Software instructional approach should be reexamined thoroughly when more data become available.

People interested in adopting digital tools to help children with MD should be also aware of the enormous variability found across studies. Ongoing research is required to establish other factors associated with intervention efficacy and eventual positive and negative consequences of digital tools for learning. This acquired knowledge should hopefully provide evidence-based criteria to select high-quality programs and to deliver appropriate interventions to the students with low-numeracy.

6. Limitations

It should be noted that this analysis is based on 15 randomized-controlled trials, which met the criterion for this study. They cannot be extended to single-subject designs that often show more powerful results than those with a group design. Indeed, in single-subject designs the training is usually only stopped when the results are sufficiently high. Large effect sizes under such circumstances are thus expected (Kroesbergen & Van Luit, 2003).

Another important factor that should be taken into consideration when interpreting the present results is the enormous variation found across studies, as indicated by the significant index of heterogeneity and the large confidence intervals. Previous studies focusing on digital-based interventions only (e.g Seo & Bryant, 2009), or interventions for children with difficulties in mathematics (e.g Chodura et al., 2015), also reported a high variation of the effect sizes. This variability across studies prevents strong conclusions and generalizations of the effectiveness of digital interventions for children with mathematical difficulties. Indeed, although a medium positive effect was found on average, some individual interventions resulted in small effect sizes or even negative ones (see the forest plot on Fig. 2). This calls for an in-depth analysis and for a careful interpretation of the results.

A major point concerns the different criteria used across studies to classify students with or at risk for learning difficulties in mathematics. All but two studies (Mohd Syah et al., 2016; Stultz, 2013) selected their participants through individual standardized math achievement tests. The tests varied across studies (e.g. Test of Early Mathematics Ability, Early Numeracy Test, Star Math, Heidelberger Rechen Test, etc.) and so did the tasks chosen for sample selection (e.g. arithmetics only, additions only, full battery, etc.). Most critically, performance of the selected children ranged from the lowest 7–10% of distribution (e.g. de Castro et al., 2014; Käser et al., 2013; Salminen et al., 2015) to the 25th (i.e Baroody et al., 2012, 2013; Burns et al., 2012; Fuchs et al., 2006; Nelson et al., 2013) and up to the 45th and 50th percentile (Hassler Hallstedt et al., 2018; Leh & Jitendra, 2013, respectively), suggesting that in some cases also students in the average range performance were included. The majority of studies concurred on excluding participants with psychiatric, physical, and neurological problems. Only two (de Castro et al., 2014; Mohd Syah et al., 2016) reported using also the criterion of no response to intervention of the DSM edition approved in 2013 (American Psychiatric Association, 2013). The studies that intervened on at-risk samples (e.g. Aunio & Mononen, 2018; Baroody et al., 2013, 2012; Fuchs et al., 2006) also included participants that, besides showing low performance on the standard achievement tests, were exposed to disadvantaged contextual situations.

Hence, the heterogeneity found on the effect sizes may at least in part reflect the different characteristics of the children, who were nevertheless all selected and treated for having MD. These huge variations on the selection criteria are problematic for the generalization and interpretation of the results but might not be unexpected. Independent authorities use different terminologies and different basis for diagnosing dyscalculia/mathematical learning difficulties across countries (e.g. International Classification of Diseases; Diagnostic and Statistical Manual of Mental Disorders, etc.), and even single authorities (e.g. the American Psychiatric Association in the USA) modify their official definitions throughout the years (e.g. DSM-IV; DSM-5). The practical and theoretical implications of using different selection criteria have been pointed out in previous works (e.g. Butterworth, 2019; Devine et al., 2013). Adhering to the proposal of adopting international standard diagnostic tools that are comparable across countries, curricula and therefore studies (Kaufmann et al., 2013), seems reasonable and advisable in this regard.

Results of the present meta-analysis are dependent on the quality of the measures used in the primary studies. Adopting appropriate measures to evaluate participants performance is problematic when the target group is selected from the lower tail of the population distribution (as in the case of mathematical ability in children with MD). In this situation, the floor effect and the regression to the mean (RTM) could influence the results leading to an incorrect estimation of the actual effects (Simkovic & Trauble, 2019). In almost half of the studies included in the meta-analysis (Baroody et al., 2013, 2012; de Castro et al., 2014; Fuchs et al., 2006; Salminen et al., 2015; Stultz, 2013) there are clues of the presence of the floor effect. Moreover, the studies reported mean values smaller than the standard deviation, indicating that the measures did not properly catch the whole range of individual differences. Moreover, in Mohd Syah et al. (2016) mean scores differences between intervention and control groups at pre-test do not allow us to exclude that results were caused by the RTM effect (see supplemental material for raw data of each study). Altogether these considerations preclude from drawing strong conclusions when interpreting results of the present meta-analysis. Effects of the above cited studies, if caused by floor effect and RTM effect, could be an excesive estimate of the true underlying effect and, as a consequence, may lead to an overestimation in the results of the meta-analysis. Although the sensitivity analysis showed that the results are not affected by single influential studies, this would not be the case if an entire set of studies –which nevertheless show important evidence about the direction of the effect, and represent a large part of evidence– were excluded.

7. Directions for future research

Some other features of the programs and or experimental designs might be taken into consideration in future studies to better understand the potentialities of the various digital-based interventions. For example, one possible factor to take into account could be the type of control group. One might expect larger effect sizes in studies comparing experimental versus passive control groups than in studies comparing experimental and active control interventions. In our study we noticed that most of the studies with videogame interventions used also a passive control group (5 out of 6), whereas most of the studies with tutorials and drill & practice approaches used an active control group (5 out of 6). Thus, larger effects could have been anticipated in the videogame interventions. Because of interdependence between the control and the software instructional approach, it was impossible to evaluate the relative role of these variables as moderators independently. However, it will be appropriate in the future, when more primary studies become available, to further investigate the effects of the control group in the reported effectiveness of the interventions.

Similarly, other characteristics of the intervention, such as duration and topic of intervention (i.e. problem solving, number sense, math facts, fractions, arithmetic, etc.) could provide more practical and theoretical insights into the effects and appropriateness of using digital-based tools at different stages of the mathematical learning path. These characteristics were not included in the moderator analysis of the present study due to high variability in the levels of each factor.

Another important note for future studies is to carefully consider the choice of instruments used to evaluate mathematical performance in children with MD in order to avoid issues related to floor effect and regression to the mean. Although this requires a big effort, we believe that the development of instruments that properly evaluate variation in individual differences among low performance children should be encouraged to obtain more reliable and informative results.

Finally, although it is central to analyze the benefits of the interventions focusing on mathematical achievement, in the future it will be valuable to systematically review and meta-analyze the emotional and motivational effects associated with playing and using digital tools, whether they differ as a function of the instructional approach (e.g. games versus drilling), and the extent to which this impacts on the learning process.

Open practices

The code to reproduce the analyses reported in this article has been made publicly available via the Supplemental Materials.

Declaration of competing interest

The authors declare no conflicts of interest.

Acknowledgments

S.B.V was founded by the Italian Ministry of Instruction, University and Research "Progetti di Rilevante Interesse Nazionale (PRIN)" (Prot. 2017PSRHPZ) and by the University of Padua under the STARS Grants programme (MINI).t

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compedu.2020.103953.

References

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (DSM-5®)*. American Psychiatric Pub.

Arcara, G, Burgio, F, Benavides-Varela, S, Toffano, R, Gindri, P, Tonini, E, & Semenza, C (2017). Numerical activities of daily living–financial (NADL-F): a tool for the assessment of financial capacities. *Neuropsychological Rehabilitation, 29*(7), 62–84. https://doi.org/10.1080/09602011.2017.1359188.

Ashcraft, M. H., & Ridley, K. S. (2005). Math anxiety and its cognitive con- sequences. In J. I. D. Campbell (Ed.), *Handbook of mathematical cognition* (pp. 315–327). New York, NY: Psychology Press.

Aunio, P. (2019). Chapter 8 - early numeracy skills learning and learning difficulties—evidence-based assessment and interventions. In D. C. Geary, D. B. Berch, & K. Mann Koepke (Eds.), *Cognitive foundations for improving mathematical learning* (1st ed., pp. 195–214). Academic Press volume 5 of *Mathemat- ical Cognition and Learning*. https://doi.org/10.1016/B978-0-12-815952-1 10.1016/B978-0-12-815952-1.00008-6.

Aunio, P., & Mononen, R. (2018). The effects of educational computer game on low-performing children's early numeracy skills–an intervention study in a preschool setting. *European Journal of Special Needs Education, 33*, 677–691. https://doi.org/10.1080/08856257.2017.1412640.

Baroody, A. J., Eiland, M. D., Purpura, D. J., & Reid, E. E. (2012). Fostering at-risk kindergarten children's number sense. *Cognition and Instruction, 30*, 435–470. https://doi.org/10.1080/07370008.2012.720152.

Baroody, A. J., Eiland, M. D., Purpura, D. J., & Reid, E. E. (2013). Can computer-assisted discovery learning foster first graders' fluency with the most basic addition combinations? *American Educational Research Journal, 50*, 533–573. https://doi.org/10.3102/0002831212473349.

Benavides-Varela, S, Burgio, F, Meneghello, F, De Marco, M, Arcara, G, Rigon, J, … Semenza, C (2015). Anatomical substrates and neurocognitive predictors of daily numerical abilities in mild cognitive impairment. *Cortex, 71*, 58–67. https://doi.org/10.1016/j.cortex.2015.05.031.

Benavides-Varela, S, Burgio, F, Weis, L, Mitolo, M, Palmer, K, Toffano, R, … Semenza, C (2020). The role of limbic structures in financial abilities of mild cognitive impairment patients. *Neuroimage: Clinical*, 102222. https://doi.org/10.1016/j.nicl.2020.102222.

Benavides-Varela, S, Butterworth, B, Burgio, F, Arcara, G, Lucangeli, D, & Semenza, C (2016). Numerical activities and information learned at home link to the exact numeracy skills in 5–6 years-old children. *Frontiers in Psychology, 7*, 94. https://doi.org/10.3389/fpsyg.2016.00094.

Benavides-Varela, S, Piva, D, Burgio, F, Passarini, L, Rolma, G, Meneghello, F, & Semenza, C (2017). Re-assessing acalculia: Distinguishing spatial and purely arithmetical deficits in right-hemisphere damaged patients. *Cortex, 88*, 151–164. https://doi.org/10.1016/j.cortex.2016.12.014.

Borenstein, M., Hedges, L. V., Higgins, J. P., & Rothstein, H. R. (2009). *Intro- duction to meta-analysis*. John Wiley & Sons.

Brunda, A., & Bhavithra, J. (2010). Adaptive computer assisted instruction (CAI) for students with dyscalculia (learning disability in mathematics). In *Proceedings of the 1st amrita ACM-W celebration on women in computing in India A2CWiC '10* (pp. 12:1–12:7). New York, NY, USA: ACM. https://doi.org/10.1145/1858378.1858390.

Bryant, D. P., Bryant, B. R., Roberts, G., Vaughn, S., Pfannenstiel, K. H., Porterfield, J., & Gersten, R. (2011). Early numeracy intervention program for first-grade students with mathematics difficulties. *Exceptional Children, 78*, 7–23. https://doi.org/10.1177/001440291107800101.

Burns, M. K., Kanive, R., & DeGrande, M. (2012). Effect of a computer- delivered math fact intervention as a supplemental intervention for math in third and fourth grades. *Remedial and Special Education, 33*, 184–191. https://doi.org/10.1177/0741932510381652.

Butterworth, B. (2019). *Dyscalculia from science to education*. Routledge Taylor & Francis Group. https://lccn.loc.gov/2018033493.

Butterworth, B., & Laurillard, D. (2010). Low numeracy and dyscalculia: Identification and intervention. *ZDM Mathematics Education, 42*, 527–539. https://doi.org/10.1007/s11858-010-0267-4.

Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: From brain to education. *Science, 332*, 1049–1053. https://doi.org/10.1126/science.1201536.

de Castro, M. V., Bissaco, M. A. S., Panccioni, B. M., Rodrigues, S. C. M., & Domingues, A. M. (2014). Effect of a virtual environment on the development of mathematical skills in children with dyscalculia. *PloS One, 9*, Article e103354. https://doi.org/10.1371/journal.pone.0103354.

Cezarotto, M. A., & Battaiola, A. L. (2016). Game design recommendations focusing on children with developmental dyscalculia. In *International conference on learning and collaboration technologies* (pp. 463–473). Springer. https://doi.org/10.1007/978-3-319-39483-1_42.

Chodura, S., Kuhn, J.-T., & Holling, H. (2015). Interventions for children with mathematical difficulties. *Zeitschrift fur Psychologie, 223*, 129–144. https://doi.org/10.1027/2151-2604/a000211.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Erlbaum.

Dempsey, J. V., Rasmussen, K., & Lucassen, B. (1994). Instructional gaming: Implications for instructional technology. In *Annual meeting of the associa- tion for educational communications and technology* (pp. 16–20). February 1994 . Nashville, TN https://eric.ed.gov/?id=ED368345.

Devine, A., Solt′esz, F., Nobes, A., Goswami, U., & Szu″cs, D. (2013). Gender differences in developmental dyscalculia depend on diagnostic criteria. *Learning and Instruction, 27*, 31–39. https://doi.org/10.1016/j.learninstruc.2013.02.004.

Dowker, A. (2017). Interventions for primary school children with difficulties in mathematics. In J. Sarama, D. H. Clements, C. Germeroth, & C. Day-Hess (Eds.), *Advances in child development and behavior* (Vol. 53, pp. 255–287). Elsevier. https://doi.org/10.1016/bs.acdb.2017.04.004.

Drigas, A. S., Pappas, M. A., & Lytras, M. (2016). Emerging technologies for ICT based education for dyscalculia: Implications for computer engineering education. *International Journal of Engineering Education, 32*, 1604–1610. https://www.researchgate.net/profile/Marios_Pappas/publication/309922334_Emerging_technologies_for_ICT_based_education_for_dyscalculia_Implications_for_computer_engineering_education/links/582ed5ea08aef19cb81521a2.pdf. ICT_based_education_for_dyscalculia_Implications_for_computer_ engineering_education/links/582ed5ea08aef19cb81521a2.pdf.

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., Brooks-Gunn, J., et al. (2007). School readiness and later achievement. *Developmental Psychology, 43*, 1428–1446. https://doi.org/10.1037/0012-1649.43.6.1428.

Durkin, K., Boyle, J., Hunter, S., & Conti-Ramsden, G. (2015). Video games for children and adolescents with special educational needs. *Zeitschrift fur Psychologie, 221*, 79–89. https://doi.org/10.1027/2151-2604/a000138.

Duval, S., & Tweedie, R. (2000). Trim and fill: A simple funnel-plot–based method of testing and adjusting for publication bias in meta-analysis. *Biometrics, 56*, 455–463. https://doi.org/10.1111/j.0006-341X.2000.00455.x.

Fritz, A., Haase, V. G., & Rasanen, P. (2019). *International handbook of mathematical learning difficulties: From the laboratory to the classroom*. Switzerland: Springer International Publishing. https://doi.org/10.1007/978-3-319-97148-3.

Fuchs, L. S., Fuchs, D., Hamlet, C. L., Powell, S. R., Capizzi, A. M., & Seethaler, P. M. (2006). The effects of computer-assisted instruction on number com- bination skill in at-risk first graders. *Journal of Learning Disabilities, 39*, 467–475. https://doi.org/10.1177/00222194060390050701.

Geary, D. C. (2011). Cognitive predictors of achievement growth in mathemat- ics: A 5-year longitudinal study. *Developmental Psychology, 47*, 1539–1552. https://doi.org/10.1037/a0025510.

Geary, D. C., Hoard, M. K., & Bailey, D. H. (2012). Fact retrieval deficits in low achieving children and children with mathematical learning disability. *Journal of Learning Disabilities, 45*, 291–307. https://doi.org/10.1177/0022219410392046.

Gee, J. P. (2003). What video games have to teach us about learning and literacy. *Computer Entertainment, 1*. https://doi.org/10.1145/950566.950595, 20–20.

Ginsburg, H., & Baroody, A. (2003). *Test of early mathematics ability* (3rd ed.). Austin, TX: Pro-Ed.

Ginsburg, H. P., Jamalian, A., & Creighan, S. (2013). Cognitive guidelines for the design and evaluation of early mathematics software: The example of MathemAntics. In L. English, & J. Mulligan (Eds.), *Reconceptualizing early mathematics learning* (pp. 83–120). Dordrecht: Springer. https://doi.org/10.1007/978-94-007-6440-8_6.

Gouet, C., Silva, C. A. G., Guedes, B., & Peña, M. (2018). Cognitive and neural effects of a brief nonsymbolic approximate arithmetic training in healthy first grade children. *Frontiers in Integrative Neuroscience, 12*, 28. https://doi.org/10.3389/fnint.2018.00028.

Hassler Hallstedt, M., Klingberg, T., & Ghaderi, A. (2018). Short and long- term effects of a mathematics tablet intervention for low performing second graders. *Journal of Educational Psychology, 110*, 1127–1148. https://doi.org/10.1037/edu0000264.

Hedges, L. V., & Olkin, I. (2014). *Statistical methods for meta-analysis*. Aca- demic press.

Jitendra, A. K., Lein, A. E., Im, S.-h., Alghamdi, A. A., Hefte, S. B., & Mouanoutoua, J. (2018). Mathematical interventions for secondary students with learning disabilities and mathematics difficulties: A meta-analysis. *Exceptional Children, 84*, 177–196. https://doi.org/10.1177/0014402917737467.

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology, 45*, 850. https://doi.org/10.1037/a0014939.

Karagiannakis, G., Baccaglini-Frank, A., & Papadatos, Y. (2014). Mathematical learning difficulties subtypes classification. *Frontiers in Human Neuroscience, 8*, 57. doi: 10.3389/fnhum.2014.00057.

Käser, T., Baschera, G.-M., Kohn, J., Kucian, K., Richtmann, V., Grond, U., & von Aster, M. (2013). Design and evaluation of the computer- based training program calcularis for enhancing numerical cognition. *Frontiers in Psychology, 4*, 489. https://doi.org/10.3389/fpsyg.2013.00489.

Kaufmann, L., Mazzocco, M. M., Dowker, A., von Aster, M., Goebel, S., Grab- ner, R., Henik, A., Jordan, N. C., Karmiloff-Smith, A. D., Kucian, K., Ru- binsten, O., Szucs, D., Shalev, R., & Nuerk, H.-C. (2013). Dyscalculia from a developmental and differential perspective. *Frontiers in Psychology, 4*, 516. doi:10.3389/fpsyg.2013.00516.

Kroeger, L. A., Brown, R. D., & O'Brien, B. A. (2012). Connecting neuroscience, cognitive, and educational theories and research to practice: A review of mathematics intervention programs. *Early Education & Development, 23*, 37–58.

Kroesbergen, E. H., & Van Luit, J. E. (2003). Mathematics interventions for children with special educational needs: A meta-analysis. *Remedial and Special Education, 24*, 97–114. https://doi.org/10.1177/07419325030240020501.

Kucian, K., Grond, U., Rotzer, S., Henzi, B., Schonmann, C., Plangger, F., Galli, M., Martin, E., & von Aster, M. (2011). Mental number line training in children with developmental dyscalculia. *NeuroImage, 57*, 782–795. https://doi.org/10.1016/j.neuroimage.2011.01.070.

Kulik, J. A. (1994). Meta-analytic studies of findings on computer-based instruction. In E. L. Baker, & H. F. O'Neil (Eds.), *Technology assessment in education and training* (pp. 9–34). Hillsdale, NJ: Lawrence Erlbaum.

Leh, J. M., & Jitendra, A. K. (2013). Effects of computer-mediated versus teacher-mediated instruction on the mathematical word problem-solving performance of third-grade students with mathematical difficulties. *Learning Disability Quarterly, 36*, 68–79.

Li, Q., & Ma, X. (2010). A meta-analysis of the effects of computer technology on school students' mathematics learning. *Educational Psychology Review, 22*, 215–243. https://doi.org/10.1007/s10648-010-9125-8.

López-Morteo, G., & López, G. (2007). Computer support for learning mathe- matics: A learning environment based on recreational learning objects. *Computers & Education, 48*, 618–641. https://doi.org/10.1016/j.compedu.2005.04.014.

Mastropieri, M. A., Scruggs, T. E., & Shiah, S. (1991). Mathematics instruction for learning disabled students: A review of research. *Learning Disabilities Research & Practice, 6*, 89–98. https://psycnet.apa.org/record/1994-19528-001.

Mazzocco, M. M. (2005). Challenges in identifying target skills for math disability screening and intervention. *Journal of Learning Disabilities, 38*, 318–323. https://doi.org/10.1177/00222194050380040701.

Mazzocco, M. M., & Räsänen, P. (2013). Contributions of longitudinal studies to evolving definitions and knowledge of developmental dyscalculia. *Trends in Neuroscience and Education, 2*, 65–73. https://doi.org/10.1016/j.tine.2013.05.001.

Miller, S. P., Butler, F. M., & Kit-hung, L. (1998). Validated practices for teaching mathematcis to students with learning disabilities: A review of literature. *Focus on Exceptional Children, 31*, 1–24. https://search.proquest.com/openview/ccbba8a7e4230ed732a58064e6fea3bf/1?cbl=48488&pq-origsite=gscholar.

Mitchell, A., & Savill-Smith, C. (2004). *The use of computer and video games for learning: A review of the literature*. London: Learning and Skills Development Agency. OCLC: 62244824.

Mohd Syah, N. E., Hamzaid, N. A., Murphy, B. P., & Lim, E. (2016). Development of computer play pedagogy intervention for children with low conceptual understanding in basic mathematics operation using the dyscal- culia feature approach. *Interactive Learning Environments, 24*, 1477–1496. https://doi.org/10.1080/10494820.2015.1023205.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Annals of Internal Medicine, 151*, 264–269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135.

Morris, S. B. (2008). Estimating effect sizes from pretest-posttest-control group designs. *Organizational Research Methods, 11*, 364–386. https://doi.org/10.1177/1094428106291059.

Nelson, P. M., Burns, M. K., Kanive, R., & Ysseldyke, J. E. (2013). Comparison of a math fact rehearsal and a mnemonic strategy approach for improving math fact fluency. *Journal of School Psychology, 51*, 659–667. https://doi.org/10.1016/j.jsp.2013.08.003.

Outhwaite, L. A., Faulder, M., Gulliford, A., & Pitchford, N. J. (2019). Raising early achievement in math with interactive apps: A randomized control trial. *Journal of Educational Psychology, 111*, 284–298. https://doi.org/10.1037/edu0000286.

R Core Team. (2019). *R: A language and environment for statistical com- puting*. Austria: R Foundation for Statistical Computing Vienna. https://www.R-project.org/.

Ramirez, G., Shaw, S. T., & Maloney, E. A. (2018). Math anxiety: Past research, promising interventions, and a new interpretation framework. *Educational Psychologist, 53*, 145–164. https://doi.org/10.1080/00461520.2018.1447384.

Ritchie, S. J., & Bates, T. C. (2013). Enduring links from childhood mathe- matics and reading achievement to adult socioeconomic status. *Psychological Science, 24*, 1301–1308. https://doi.org/10.1177/0956797612466268.

Räsänen, P., Laurillard, D., Käser, T., & von Aster, M. (2019). Perspectives to technology-enhanced learning and teaching in mathematical learn- ing difficulties. In A. Fritz, V. G. Haase, & P. Räsänen (Eds.), *Inter- national handbook of mathematical learning difficulties: From the laboratory to the classroom* (pp. 733–754). Springer International Publishing.

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

Ritchie, D., & Dodge, B. (1992). Integrating technology usage across the cur- riculum through educational adventure games. In *The annual conference on technology and teacher education, 12–15 March 1992. Houston, TX*. https://eric.ed.gov/?id=ED349955.

Rivera-Batiz, F. L. (1992). Quantitative literacy and the likelihood of employment among young adults in the United States. *Journal of Human Resources, 27*, 313–328. https://doi.org/10.2307/145737.

Rosas, R., Nussbaum, M., Cumsille, P., Marianov, V., Correa, M., Flores, P., Grau, V., Lagos, F., L′opez, X., L′opez, V., Rodriguez, P., & Salinas, M. (2003). Beyond nintendo: Design and assessment of educational video games for first and second grade students. *Computers & Education, 40*, 71–94. https://doi.org/10.1016/S0360-1315(02)00099-4.

Rothstein, H. R., Sutton, A. J., & Borenstein, M. (2005). *Publication bias in meta-analysis: Prevention, assessment and adjustments*. John Wiley & Sons, Ltd. https://doi.org/10.1002/0470870168.

Salminen, J., Koponen, T., Rasanen, P., & Aro, M. (2015). Preventive sup- port for kindergarteners most at-risk for mathematics difficulties: Computer- assisted intervention. *Mathematical Thinking and Learning, 17*, 273–295. https://doi.org/10.1080/10986065.2015.1083837.

Sella, F, Tressoldi, P, Lucangeli, D, & Zorzi, M (2016). Training numerical skills with the adaptive videogame "The Number Race": A randomized controlled trial on preschoolers. *Trends in Neuroscience and Education, 5*(1), 20–29. https://doi.org/10.1016/j.tine.2016.02.002.

Semenza, C, Meneghello, F, Arcara, G, Burgio, F, Gnoato, F, Facchini, S, … Butterworth, B (2014). A new clinical tool for assessing numerical abilities in neurological diseases: numerical activities of daily living. *Frontiers in Aging Neuroscience*, 112. https://doi.org/10.3389/fnagi.2014.00112.

Seo, Y. J., & Bryant, D. P. (2009). Analysis of studies of the effects of computer- assisted instruction on the mathematics performance of students with learning disabilities. *Computers & Education, 53*, 913–928. https://doi.org/10.1016/j.compedu.

Seo, Y.-J., & Woo, H. (2010). The identification, implementation, and evaluation of critical user interface design features of computer-assisted instruction programs in mathematics for students with learning disabilities. *Computers & Education, 55*, 363–377. https://doi.org/10.1016/j.compedu.2010.02.002.

Stanmore, E., Stubbs, B., Vancampfort, D., de Bruin, E. D., & Firth, J. (2017). The effect of active video games on cognitive functioning in clinical and non- clinical populations: A meta-analysis of randomized controlled trials. *Neuroscience & Biobehavioral Reviews, 78*, 34–43. https://doi.org/10.1016/j.neubiorev.2017.04.011. doi:10.1016/j.neubiorev.HYPERLINK.

Stultz, S. L. (2013). The effectiveness of computer-assisted instruction for teaching mathematics to students with specific learning disability. *The Journal of Special Education Apprenticeship, 2*. Article 7. URL: https://scholarworks.lib.csusb.edu/josea/vol2/iss2/7.

imkovic, M. S, & Trauble, B. (2019). Robustness of statistical methods when measure is affected by ceiling and/or floor effect. *PloS One, 14*, Article e0220889. https://doi.org/10.1371/journal.pone.0220889.

Valle-Lisboa, J., Cabana, A.′., Eisinger, R., Mailhos, A.′., Luzardo, M., Halberda, J., & Maiche, A. (2016). Cognitive abilities that mediate SES's effect on elementary mathematics learning: The uruguayan tablet-based intervention. *Prospects, 46*, 301–315. https://doi.org/10.1007/s11125-017-9392-y.

Van De Rijt, B. A. M., & Van Luit, J. E. H. (1998). Effectiveness of the additional early mathematics program for teaching children early mathematics. *Instructional Science, 26*, 337–358. https://doi.org/10.1023/A:1003180411209.

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software, 36*. doi:10.18637/jss.v036.i03.

Viechtbauer, W., & Cheung, M. W.-L. (2010). Outlier and influence diagnostics for meta-analysis. *Research Synthesis Methods, 1*, 112–125.

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

Wilson, A. J., Revkin, S. K., Cohen, D., Cohen, L., & Dehaene, S. (2006). An open trial assessment of "the number race", an adaptive computer game for remediation of dyscalculia. *Behavioral and Brain Functions, 2*, 20. https://doi.org/10.1186/1744-9081-2-20.

Woodward, J., & Carnine, D. (1993). Uses of technology for mathematics assessment and instruction: Reflection on a decade of innovations. *Journal of Special Education Technology, 12*, 38–48. https://doi.org/10.1177/016264349301200103.