Cognitive Development xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Cognitive Development

Computer-assisted intervention for children with low numeracy skills

Pekka Räsänen[a,*], Jonna Salminen[a], Anna J. Wilson[b], Pirjo Aunio[a], Stanislas Dehaene[c]

[a] Niilo Mäki Institute, Jyväskylä, Finland
[b] Department of Psychology, The University of Auckland, New Zealand
[c] INSERM, Cognitive Neuroimaging Unit, Paris, France

ARTICLE INFO

ABSTRACT

We present results of a computer-assisted intervention (CAI) study on number skills in kindergarten children. Children with low numeracy skill ($n = 30$) were randomly allocated to two treatment groups. The first group played a computer game (The Number Race) which emphasized numerical comparison and was designed to train number sense, while the other group played a game (Graphogame-Math) which emphasized small sets of exact numerosities by training matching of verbal labels to visual patterns and number symbols. Both groups participated in a daily intervention session for three weeks. Children's performance in verbal counting, number comparison, object counting, arithmetic, and a control task (rapid serial naming) were measured before and after the intervention. Both interventions improved children's skills in number comparison, compared to a group of typically performing children ($n = 30$), but not in other areas of number skills. These findings, together with a review of earlier computer-assisted intervention studies, provide guidance for future work on CAI aiming to boost numeracy development of low performing children.

There has been growing recognition that preschool education provides a firm foundation for later school learning (Jordan, Kaplan, Ramineni, and Locuniak, 2009; Melhuish et al., 2008). School-entry mathematical skills predict later academic achievement even after family background and cognitive and socioemotional factors have been controlled (Duncan et al., 2007). A potentially powerful way to

* Corresponding author at: Niilo Mäki Institute, P.O. Box 35, 40014 University of Jyväskylä, Finland.
E-mail address: pekka.rasanen@nmi.fi (P. Räsänen).

0885-2014/$ – see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.cogdev.2009.09.003

boost school achievement in mathematics and to prevent later learning failures is to improve basic academic skills of low-achieving children prior to school (Claessens, Duncan, & Engel, 2009). However, low-achieving children often seem to benefit much less from preschool education than average and high-achieving children. Aunola, Leskinen, Lerkkanen, and Nurmi (2004) showed that from the beginning of preschool to second grade the growth of math competence was fastest among those children who entered kindergarten already equipped with a higher level of mathematical skills and it was slowest among those whose initial level was lower. There is therefore a need to develop more individualized interventions for low-achieving children to support their early learning in mathematics.

Recent neuropsychological research suggests existence of core numerical processes that are the foundation for learning basic number skills and arithmetic. For example, it has been suggested that the ability to process and compare numerical magnitudes is a key precursor of mathematical development (Dehaene, 2009; De Smedt, Verschaffel, & Ghesquiere, 2009) and that arithmetical skills depend on children's increasing skill in manipulating numerosities in a similar way as phonological processing is important for reading development (Gelman & Butterworth, 2005; Butterworth, 2005). These models of early numerical development give us new ideas as to how early interventions could be constructed.

In this article we present a controlled study in which we used two different types of CAI games to support early number development. The games are based on different ideas of core numerical processes.

1. Difficulties in learning mathematics

In clinical practice difficulty in learning mathematics has many faces. Typically children with mathematical difficulties struggle in learning basic arithmetic and calculation procedures (Cawley, Parmar, Yan, & Miller, 1998; Cumming & Elkins, 1999; Geary, 2004; Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Hanich, Jordan, Kaplan, & Dick, 2001; Janssen, De Boeck, Viaene, & Vallaeys, 1999; Jordan & Hanich, 2003; Jordan, Hanich, & Kaplan, 2003). They are also slower in basic numerical processing tasks, including number reading, number comparison, reciting number sequences and counting (Landerl, Bevan, & Butterworth, 2004), as well as in tasks requiring manipulation of the quantitative meaning of numbers (Rousselle & Noel, 2007) and even in subitizing small quantities (Koontz & Berch, 1996). Similarly, problems in more general number skills, including poor problem solving strategies (Lucangeli, Tressoldi, & Cendron, 1998; Ostad, 1998; Pape & Wang, 2003; Xin, Jitendra, & Deatline-Buchman, 2005) and an ability to create and interpret visual representations of mathematical concepts (Booth & Thomas, 2000; Brown & Presmeg, 1993; Geary, 1995; Geary, Hamson, & Hoard, 2000; Hegarty & Kozhevnikov, 1999; van Garderen & Montague, 2003) have been recorded.

Many components of cognitive processing have been connected to poor performance in mathematics. School-aged children with mathematical learning difficulties have very diverse problems with arithmetic, which appear to arise from different sources in different children (Dowker, 2005, 2008). Common problems include difficulties in controlling working memory (Andersson & Lyxell, 2007; Bull, Johnston, & Roy, 1999; Bull & Scerif, 2001; McLean & Hitch, 1999; Swanson & Jerman, 2006), and poor phonological (Andersson & Lyxell, 2007) and visuo-spatial working memory (Kyttälä, 2008; McLean & Hitch, 1999; Van der Sluis, Van der Leij, & De Jong, 2005). Difficulties in language and communication skills have very often accompanied mathematical disabilities (Baxter, Woodward, & Olson, 2001; Cawley, Parmar, Foley, Salmon, & Roy, 2001; Donlan, Cowan, Newton, & Lloyd, 2007; Fuchs & Fuchs, 2002; Hanich et al., 2001; Hegerty, Mayer, & Monk, 1995; Koponen, Mononen, Rasanen, & Ahonen, 2006; Verschaffel, De Corte, & Vierstraete, 1999).

1.1. Core disabilities in early number skills

Although mathematical difficulty can reflect itself in almost any number-related skill, some current theories suggest that these difficulties may stem from early developing, if not innate, core numerical processes connected to magnitudes. Both animals and humans share similar neural networks to process non-symbolic magnitudes (Cantlon, Brannon, Carter, & Pelphrey, 2006; Nieder & Miller, 2004). Similarly, there appear to be similarities in how early associations between magnitudes and symbols are built (Cantlon & Brannon, 2005, 2006; Diester & Nieder, 2007). It has been suggested that children acquire the meaning of cultural number symbols via mapping the numbers in the number sequence onto non-symbolic representations of numerical magnitude (Ansari, 2008).

Recent neuroimaging data support this assumption. In both adults and children there appear to be specific brain areas in the prefrontal cortex and in the intraparietal sulcus (IPS) that are associated with this core number processing (Cantlon et al., 2006). These brain areas are suggested to play different roles in core numerical processes at different phases of development. The role of IPS in both symbolic and non-symbolic numerical magnitude processing seems to increase with age (Ansari, Garcia, Lucas, Hamon, & Dhital, 2005; Cohen Kadosh, Lammertyn, & Izard, 2008).

Dysfunctions of IPS have been linked to acalculia in acquired brain damage (Dehaene, Piazza, Pinel, & Cohen, 2003) as well as in mathematical difficulties in children (Price, Holloway, Räsänen, Vesterinen, & Ansari, 2008). Using functional neuroimaging, Price and colleagues found that school-aged children with specific mathematical difficulties failed to show the typical specialization of these parietal brain circuits for the processing of numerical magnitude. This suggests specific abnormalities in the functional neuroanatomy underlying numerical magnitude processing in severe mathematical learning difficulties. Other studies have shown neuroanatomical correlates with numerical difficulties within the same intraparietal areas (Isaacs, Edmonds, Lucas, & Gadian, 2001; Molko et al., 2003; Rotzer et al., 2008; however, cf. Kucian et al., 2006).

Currently there are many conceptions of the innate basis for numerical abilities. On the one hand, it has been proposed that infants are equipped only with a sense of approximate magnitudes (Feigenson, Dehaene, & Spelke, 2004), upon which the concepts of exact numerosities are constructed with the aid of language (Carey, 2004). This sense later forms the basis of arithmetic (Lemer, Dehaene, Spelke, & Cohen, 2003). On the other hand, it is claimed that infants possess a 'number module' that enables them to construct concepts of the exact numerosities of sets, upon which arithmetic develops (Butterworth, 1999; Gelman & Gallistel, 1978). Yet an alternative account states that children with mathematics learning disabilities have difficulty in accessing number magnitude from symbols rather than in processing magnitudes *per se* (Rousselle & Noel, 2007). There is no consensus as to which of these theories is most accurate.

1.2. *Predicting development of early number skills*

Although research on early numerical skills is in its infancy, there has been an increasing interest in studies on predicting later school success in mathematics from variables measured at school entry or preschool age. In these studies it has been more typical to use composite scores from different types of tasks to predict later achievement, rather than estimating how well certain subskills explain future success. The rationale for this approach has been that composite scores contain a larger variance and thus tend to be better predictors of future skills than individual variables do. Moreover, although individuals may show large variation across different subskills (Dowker, 2005), in general the correlation among subskills is high, and statistically, it is arguably preferable to use one factorial solution, i.e. a composite score, as a predictor.

This composite of early numerical skills is often called *number sense* (Berch, 2005). Based on their results Jordan, Kaplan, Locuniak, and Ramineni (2007) and Jordan, Kaplan, Nabors Olah and Locuniak (2006) suggest that a number sense battery should comprise four types of tasks: magnitude comparison (which digit in a pair is larger or smaller), counting (verbal or object), identification of numbers and simple arithmetic. The skills to discriminate between quantities, to identify numbers, and to master number sequences at the end of kindergarten all have been strong predictors of mathematics outcomes at the end of first grade (Desoete & Grégoire, 2006; Clarke & Shinn, 2004; Chard et al., 2005). Jordan et al. (2007) showed that number sense performance in kindergarten, as well as number sense growth, could account for up to two thirds of the variance in first-grade math achievement. Studies also have shown that early number skills predict mathematics outcomes over and above general cognitive skills, such as verbal and spatial skills or working memory (Locuniak & Jordan, 2008; Mazzocco & Thompson, 2005).

Mazzocco and Thompson (2005) took another approach to this question by analyzing which items from the TEMA-2 subscales predicted mathematics from kindergarten to third grade. They found that tasks that measured counting objects were powerful predictors of later occurring mathematical learning difficulties. VanDerHeyden, Broussard, and Cooley (2006) reported that various verbal counting skills are needed in development of counting numerosity of sets. Also Aunola et al. (2004) showed that the level of mathematical performance and its growth at school age could be predicted by children's counting ability at preschool age.

Recently, De Smedt et al. (2009) showed that even very basic number comparison performance in first grade predicted later mathematical skills, but the same was not found for number reading. Similarly, Halberda, Mazzocco, and Feigenson (2008) showed that magnitude comparison correlated strongly with standardized math test results. In their retrospective study they measured the acuity to discriminate dot patterns in 14-year-olds. Performance correlated with standardized math test results collected from these same children at ages 5–11.

Together, these studies suggest that a low starting level is predictive of failure to progress (Aubrey & Godfrey, 2003; Aubrey, Dahl, & Godfrey, 2006; Jordan et al., 2003).

2. Computer-assisted interventions

Since the 1960s, computerized technologies have changed dramatically the ways in which children interact with information. They read more from computer and mobile phone screens than from printed books and play more computer games than watch television (Christakis, Ebel, Rivara, & Zimmerman, 2004). When facing a number problem in everyday life, they pick up their mobile phone calculator instead of calculating in their heads (Wilska, 2003). Therefore it is surprising that computer games have not achieved a larger role in education and educational research, even though computer assisted instruction/intervention (CAI) has for some time been alleged to surpass paper-and-pencil owing to features such as visual/action superiority (Pezdek & Stevens, 1984), graphic animation (Hayes, Chemelski, & Birnbaum, 1981), extended attention span (Clements, 1994), and feedback (Azevedo & Bernard, 1995; Grover, 1986; Vasilyeva, Puuronen, Pechenizkiy, & Räsänen, 2007).

As stated by Vernadakis, Avgerinos, Tsitskari, and Zachopoulou (2005), "CAI programmes may never replace the book and the blackboard but one should be aware are that they are more accessible by young children, who learn better with pictures and sounds, and the proper use of appropriate programmes could make a considerable difference." (p. 99). Still, some researchers express reservations about using computers in education: One reason is a lack of well-controlled studies. Moreover, results from studies on using computer games as learning media have been inconsistent. In addition, research on CAI has usually not accounted for different instructional methods and content materials. Even more, separating treatment and novelty effects has turned out to be very difficult.

2.1. *What is computer-assisted intervention (CAI)?*

The idea of having mechanical machines facilitate learning or even carry out instruction is far from a new one. The first patents for mechanical educational tools in mathematics were accepted already in the 1800s (Benjamin, 1988), but without doubt there have been many ancestral assistive technologies for learning and doing calculations using finger systems, pebbles, tallies and abacuses from the beginning of numerical human life (Bogoshi, Naidoo, & Webb, 1987).

Whether these tools can be considered as real teaching machines depends on definition. Typically three requirements have been regarded as important: (1) The machine must presents information in the form of a task, (2) it must provide some means to respond, and (3) it must provide feedback about the correctness of the response (Morrill, 1961). The new possibilities of automated computing enable us to include two other requirements: (4) The system should be able to adapt the task conditions online to maximize learning, and (5) when an error occurs, the system should give feedback that minimizes the probability of failure next time. It is still a matter of debate whether any or all current computerized teaching systems meet these requirements.

The most common forms of computer programs for teaching mathematics have involved simple drill-and-practice tasks in which the machine gives a calculation task, the subject is required to reply, and the machine gives feedback about the correctness of the answer. Research on this kind of CAI started on a larger scale in the 1960s when the Institute for Mathematical Studies in the Social Sciences at Stanford (IMSSS) conducted CAI projects involving thousands of students.

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2.2. Methodological questions in CAI research

Clark (1983) put forward the argument that there are no learning benefits from employing any specific medium to deliver instruction. According to Clark, media itself does not influence learning under any conditions, but results favoring one medium over another are due to the method or content that is introduced along with the medium. Whether we can differentiate the effects of medium used, instructional method and content is a critical question. The cumulative database of results from several studies may shed some light on this question.

The importance of small-scale controlled studies increases when they are combined in a meta-analysis (Fitz-Gibbon, 1985). Sampling characteristics, study setting, and timing frequently influence results of a single study. As a consequence, the comprehensive investigation of an area, such as early intervention and learning mathematics, requires the combination of results from several individual controlled studies.

Currently, true experiments in the field of CAI are limited. Most studies have been descriptive and quasi-experimental (Goodwin, Goodwin, & Garel, 1986). Additional problems in research design include small sample sizes (Clements & Gullo, 1984; Hungate, 1982: Williams, 1984), inappropriate treatments (Goodwin, Goodwin, Nansel, & Helm, 1986; Williams, 1984), nonrepresentative samples (Buckleitner & Hohmann, 1987; Hungate, 1982), and lack of control groups (Anselmo & Zinck, 1987; Hughes & Macleod, 1986; Wilson, Dehaene, et al., 2006; Wilson, Revkin, et al., 2006).

Divergent results may occur because researchers have used different CAI games, which very often have been designed for a specific study and are not available to other researchers to replicate the studies. Moreover, researchers have examined diverse outcome measures, ranging from exam performance to learning attitudes. These factors complicate comparison across studies.

Thus in the current state of research it is difficult to reliably estimate the effectiveness of CAI for preschool aged children with mathematical learning difficulties. A high-quality intervention study should include testing before and after the intervention, an adequate control group, random assignment of participants to condition, and a sufficient number of participants. Standardized or criterion-based tests should be used, for both specific learning and broader transfer. Follow-up testing to examine how well the skills are retained is also desirable. The effectiveness of this kind of intervention is typically measured by effect size (the ratio of the improvement to the standardized variance (Cohen, 1988).

2.3. Promising results from studies of CAI

Since the 1960s several studies have claimed positive outcomes of using CAI, including premathematical knowledge (Hasselbring, Goin, and Bransford, 1988; Howard, Eatson, Brinkley, & Ingels-Young, 1994), counting skills (Hungate, 1982; Clements & Nastasi, 1993), recognizing numerals (Hungate, 1982; McCollister, Burts, Wright, & Hildreth, 1986), learning numerical concepts (Grover, 1986), as well as improvement in standardized tests of number skills (Elliot & Hall, 1997; Hughes & Macleod, 1986). The largest gains in the use of CAI have been in primary grade children's mathematics, especially when used as additional practice (Ragosta, Holland, & Jamison, 1981; Lavin & Sanders, 1983; Niemiec & Walberg, 1984, 1987).

When the target skills have been focused, even short interventions have been successful. Kraus (1981) reported a study in which second graders with only an average of one hour of computer game playing over a two-week period responded correctly to twice as many items on an addition facts speed test as did students in the control group. Based on their results Clements and Nastasi (1993) estimated that even 10 min of daily practice is sufficient for significant gains.

Similar positive outcomes in mathematics learning have been found in studies in which CAI has been used with broader content. Fletcher-Flinn and Gravatt (1995) reported that CAI was more effective than traditional instruction for a wide range of skills in maths, science, art, reading, and writing. CAI effectiveness was demonstrated for preschool and elementary as well as special education. However, in CAI studies by Moxley, Warash, Coffman, Brinton, and Concannon (1997), Din and Calao (2001), McDermott and Watkins (1983), Reitsma and Wesseling (1998), and Shute and Miksad (1997) children did show improvement in reading related skills, but no differences were found in the development of mathematical skills, compared to traditional methods.

Only a few studies have directly compared different types of CAI. Okolo (1992) and Christensen and Gerber (1990) both contrasted CAI on number combinations in a game-like format to CAI in a simple drill format. For students with learning disabilities in grades 3–6, Okolo found no significant differences between groups, but both groups improved their number combination competence. Investigating a similar question in grades 4–6, Christensen and Gerber found that students with learning disabilities were disadvantaged by the game-like format. Unfortunately, neither study incorporated a control group to verify whether the CAI condition improved more than would have been expected by just repeating the assessments. In their study with preschool children at risk for early learning difficulties, Elliot and Hall (1997) did have two groups who used computer based math activities and a third group with non-computer-based math activities. Those who used CAI scored significantly higher on a test of early mathematical ability.

2.4. *Effectiveness of CAI*

Early meta-analytic studies of CAI were published prior to the microcomputer revolution, beginning in the late 1970s. These studies reported significant improvements for students in elementary and secondary schools on computational arithmetic skills, with effect sizes (ES) ranging from 0.37 to 0.42 (Burns, 1981; Hartley, 1978). In the 1980s both mainframe machines and microcomputers were used in CAI studies. However, the appearance of more advanced personal computer technology did not change the effect sizes. For example Kulik (Kulik & Kulik, 1991; Kulik, 1994) calculated an average ES of 0.47 for math learning via CAI for elementary school. In the 1990s meta-analytic studies almost exclusively included CAI studies in which microcomputers were used. In general, positive outcomes were found for students with CAI experiences. The ESs for these meta-analyses ranged from 0.13 to 0.8 in favor of CAI groups (Fletcher-Flinn and GravattFletcher-Flinn & Gravatt, 1995; Khalili & Shashaani, 1994; Kulik & Kulik, 1991).

In a meta-analysis of 68 studies related to instructional gaming, Randel, Morris, Wetzel, and Whitehall (1992) found that 36 reported no learning advantage to using games, 22 reported students using games outperformed their classmates, while 3 studies found differences favoring traditional instruction. Similarly Dempsey, Rasmussen, and Lucassen (1996) found contradictory results concerning the educational effectiveness of CAI games.

CAI effectiveness has been compared to effectiveness found with other instructional methods to teach mathematics. In their meta-analyses Kroesbergen and van Luit (2003) and Malofeeva (2005) concluded that a computer was less effective than a teacher in assisting learning. Only Xin and Jitendra (1999) reported that CAI was the most effective method. However, Xin and Jitendra (1999) analyzed only mathematical problem solving, and, like most of the studies, did not restrict their analysis to preschool age and early number skills.

Only a few CAI studies of early number skills have reported results in sufficient detail to enable numerical comparisons between intervention and control groups. With a rather comprehensive database search we found five studies on CAI with young children which presented both pre- and post-test scores with standard deviations for both experimental and control groups (Christensen & Gerber, 1990; Clements, 1986; Fuchs et al., 2006; Ortega-Tudela & Gómez-Ariza, 2006; Shin et al., 2006). Although all these studies had very different types of aims, groups and measures, the figures presented allowed us to produce comparable “benchmark values” for different types of CAI on early number skills (Table 1).

Clements (1986) randomly divided 72 6–8-year-olds from typically performing class rooms into three groups. One played LOGO, one group used 18 different commercial computer games for mathematics, reading and problem solving, and one group acted as a control group. The aim of this 22-week intervention study was to assess development in metacognitive skills, but measures of classification and seriation were also collected. Fuchs et al. (2006) compared the number combination skills of at-risk first graders in an 18-week intervention study in which a randomly assigned intervention group ($n = 16$) used mathematics flash cards while a control group ($n = 17$) used reading flash cards. The aim was to improve children’s addition and subtraction fluency. Ortega-Tudela and Gómez-Ariza (2006) studied whether 21 weeks of CAI would produce better results in learning cardinality than the same material in a printed format with a group of 18 six-year-olds with Downs syndrome. Shin et al. (2006)

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Table 1
Effect sizes with sample size correction (Hedges and Olkin, 1985) and confidence intervals for effect sizes calculated from the difference in gains between CAI and control groups in five studies.

Study	*n*	Task	Effect Size	Confidence Interval for Effect Size	
				Lower	Upper
Ortega-Tudela and Gómez-Ariza (2006)	18	Correspondence	0.86	−0.11	1.83
		Stabile order (10)	1.33	0.30	2.36
		Cardinality	0.91	−0.06	1.89
		Stabile order (20)	1.38	0.35	2.42
		Give X	2.88	1.56	4.21
Christensen and Gerber (1990)	30	Written addition, LD	0.61	−0.12	1.34
		Written addition, ND	0.41	−0.31	1.14
		Oral addition, LD (time)	0.52	−0.21	1.24
		Oral addition, ND (time)	−0.05	−0.76	0.67
Clements (1986)	24	CAI vs. Logo in Math	0.54	−0.27	1.36
		CAI vs. Control in Math	0.55	−0.27	1.36
		CAI vs. Logo in Classification	1.28	0.40	2.15
		CAI vs. Control in Classification	0.14	−0.66	0.94
		CAI vs. Logo in Seriation	1.55	0.64	2.47
		CAI vs. Control in Seriation	−0.25	−1.05	0.55
Fuchs et al. (2006)[a]	33	Addition fact	0.95	0.23	1.67
		Subtraction fact	−0.01	−0.69	0.67
		Story problems	−0.12	−0.80	0.56
Shin et al. (2006)	37	Addition and subtraction	0.29	−0.36	0.94
		Basic Addition and subtraction	0.36	−0.29	1.01
		Advanced Add. and subtraction	−0.07	−0.72	0.57
Total	184		0.67	−0.15	1.49

Note: LD: Learning disabled; ND: normal development.

[a] Fuchs et al. (2006) used the correction for the correlation between the pre- and post-measurement (see Glass, McGaw, & Smith, 1981) in their own analysis.

studied the effectiveness of hand-held computer games with 46 second graders divided into hand-held and control game groups. Christensen and Gerber (1990) used two types of single-digit addition drill-and-practice tasks, a game-like and a straightforward non-game-like repetitive task, to teach calculation fluency to 30 third to fifth graders with learning disabilities and to 30 seven-year-old nondisabled children. Children were randomly divided into experimental and control groups.

We calculated the effect sizes of these five studies by dividing the difference in gains across experimental and control conditions with the pooled standard deviation of the pre-test results. We also calculated the confidence interval (95%) by using the standard error of the effect size estimates. Although the average gain in CAI compared to control conditions showed a moderate effect size (.67) the confidence interval expanded from −.15 to 1.49.

Interestingly these estimates of improvement are rather close to those from the early IMSSS studies from the 1960s. In these early controlled studies on CAI the IMSSS group used basic drill-and-practice tasks and a rather simple "Teletype" typewriter for responding, but the system already contained logic for individualizing the progress for each child (Suppes & Morningstar, 1969). We calculated the effect sizes from the *t*-test of the gains in SAT computation score between the experimental and control groups in these IMSSS studies. An extra 5–10 min daily CAI practice for eight months produced in first to third graders a gain comparable to effect sizes from .05 to .73 in higher performing schools and from .70 to 1.28 in more deprived areas with lower performing children (Suppes, Jerman, & Brian, 1968).

In sum, although there has been a giant step in technical development affecting how educational contents can be presented, how people can interact with computer interfaces and the calculation power of modern computers compared to those of the 1960s, anecdotal evidence suggests that these

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developments have not led to similar improvements in the effectiveness of computer-assisted interventions.

2.5. Aims of the present study

In the small-scale study presented here, we analyzed the effectiveness of two different intervention approaches to computer games aiming to boost early number skills of six-year-olds showing slow development in number skills.

We selected two types of games for our study. The first, Number Race (NR; Wilson, Dehaene, et al., 2006; Wilson, Revkin, et al., 2006) is based on an idea that number skills develop from approximate representations of magnitudes, and with the aid of counting these representations are connected to numbers. The second game, Graphogame-Math (GG-M; Mönkkönen et al., in preparation) is based on the idea that learning the correspondences between small sets of objects and numbers helps the child to discover the relationships in the number system and arithmetic. The key difference between the games is that while NR stresses the importance of approximate comparison process, GG-M concentrates only on exact numerosities and number symbols.

The number range in both games is within one digit numbers and magnitudes from one to nine. Likewise, both games contain adaptive features (i.e. adjusting the level of difficulty) and give immediate and delayed feedback. Similarly, both games keep a log file containing a child's answers and reaction times, enabling in-depth analysis of the data and making them suitable for research. Finally, both games are easily available to other researchers.

To evaluate the effectiveness of the intervention with these games, we selected tasks shown to be the best predictors of later school achievement in mathematics: comparison, counting (verbal and object), and arithmetic. To determine whether playing different types of educational games would produce different types of improvement in these skills, we made standard pre-post gain comparisons across groups.

There are no previous published studies on Graphogame-M. Wilson, Dehaene, et al. (2006) and Wilson, Revkin, et al. (2006) published a five-week training study with 7–9-year-olds with mathematical learning difficulties using the Numberrace game. They found an increase in speed of subitizing by 300 ms, and increased subtraction accuracy by an average of 23%. No change in the speed of object counting (4 or more objects) was found. Desoete, Ceullemans, Royers, and Huylebroek (2009) claimed that these results showed that subitizing and number comparison could be enhanced in children with mathematical difficulties. However, Wilson, Dehaene, et al. (2006) and Wilson, Revkin, et al. (2006) did not have any control group in their study, thus a replication of their study with younger children and with a control group is needed.

The Number Race game (NR) is an open source (GNU Public License) project started by Dehaene and Wilson. It is freely available from http://sourceforge.net/projects/numberrace/. The software is written in Java and is thus multi-platform. It has been translated into seven different languages; English, Dutch, French (original version), German, Spanish, Finnish and Swedish. The full specification of the game can be found from Wilson, Revkin, et al. (2006). The NR software trains children on an entertaining numerical comparison task, by presenting problems adapted to the performance level of the individual child. The game is divided into two screens: comparison and number line. The child is instructed to select more from two options presented either as dots, numbers or as addition or subtraction tasks. When the number symbols or calculations are presented, they are at first accompanied with dot patterns. The adaptation is based on an algorithm, which relies on an internal model of the child's knowledge in a multidimensional "learning space" consisting of three difficulty dimensions: numerical distance, response deadline, and conceptual complexity (from non-symbolic numerosity processing to increasingly complex symbolic operations). In order to enhance number sense, number comparison is used as the primary task of the software. Number comparison is a simple task that draws heavily on quantity representation and that produces activity in the area of the brain thought to underlie a neuronal code for numerical quantity, the horizontal intra-parietal sulcus (HIPS). The difficulty of the task and degree of associated brain activity is modulated by numerical distance (Wilson, Revkin, et al., 2006). Difficulty is constantly adapted using a multidimensional adaptive algorithm, so that the success rate of each child stays at around 75%.

The Graphogame-Math (GG-M) game was designed in the EU funded Graphogame-project in the University of Jyväskylä. The original idea was to develop a control game for a game training phoneme to grapheme correspondence. Thus the game always has an auditory probe and the child's task is to select a correct one from 2 to 5 visual options by clicking the correct solution. The auditory probe is always a number word while the options to choose change from organized dot patterns to a combination of dot patterns and number symbols, then to number symbols and in the end to symbolic additions and subtractions. The visual targets fall down from the top of the screen. The falling speed varies according to the child's success in previous items. By controlling the number of options, the speed requirement, and number of correspondences to be learned in one cycle, the probability of correct responses is held above 75%.

An updated and improved version of the Graphogame-Math (called Numerate) in Finnish and Swedish are openly downloadable from a non-profit educational net service (www.lukimat.fi). The system with automatic data collecting is available for researchers by request.

The key difference between the two games consists in how they approach numerical learning. The NR game starts from comparison of random dot patterns with large numerical difference, and the solution process does not require any verbal mediation. The GG-M starts from small sets of organized dot patterns, which are numerically close to each other, and the comparison process requires exact knowledge of the target quantity and its correspondence with the verbal label.

3. Method

3.1. Participant

The participant selection was dual-phased. First, we asked all parents whose child was in any of our 12 collaborator preschools (about 350 children) for written permission for the child to participate in the study. From those children given permission we asked the kindergarten teachers to identify children who would need special support in their early mathematical skills. These children ($n = 30$) formed the experimental group. For each of these children we selected from the same preschool groups a child whose birthday was the closest. These latter children formed the control group. In the next step, we randomly split the intervention group into two and used the first pretesting results to confirm the equal starting level of math skills in the intervention groups and randomly assigned the two groups to the two interventions. The control group without identified need for special support in early mathematical skills did not receive treatment other than the assessments. All children underwent preschool education in mathematics during the time of the intervention. In the preschool curriculum, numbers are introduced to the children, but the main focus is on more general skills of classification, seriation, and comparison, and no paper-and-pencil arithmetic is included. All children were Finnish speaking from middle or lower middle class families. One child from the control group was excluded from the analysis. The data-analysis revealed that his answers in some of the reaction time tasks were totally random, suggesting inattention. Descriptive information about the groups is presented in Table 2.

3.2. Design and materials

Two types of measures were used. We assessed verbal and spatial working memory once to get an estimate of general cognitive level. Four measures of number skills and a non-numerical control task were assessed twice before and twice after the three-week intervention period to evaluate the effectiveness of the two computerized intervention methods.

3.3. General cognitive skills

Working memory (WM) and general cognitive skills are highly related, and some analyses suggest that WM could account for as much as one half of the variance in *g* (Conway, Kane, & Engle, 2003). Similarly, working memory has been shown to be a good predictor of children numerical development (Andersson & Lyxell, 2007; Gersten, Jordan, & Flojo, 2005; Kyttälä & Lehto, 2008; McLean & Hitch, 1999; Passolunghi, Vercelloni, & Schadee, 2007; Van der Sluis et al., 2005).

Table 2
Group characteristics.

	Groups		
	Control	Graphogame-M	NumberRace
N	29	15	15
Gender (F/M)	16/13	5/10	6/9
Age (months)	78.76 (3.3)	79.40 (3.2)	77.80 (3.9)
Visual WM[a] (raw score)	6.38 (1.29)	5.07 (1.03)*	5.13 (1.19)*
Verbal WM[b] (raw score)	9.69 (2.20)	8.27 (2.43)	8.67 (2.19)
RAN[c] (*z*-score)	.47 (.70)	−.14 (.79)**	−.21 (.98)**
Playing time (min)	–	209.40 (49.46)	242.73 (54.81)
Playing sessions (*n*)	–	11.40 (2.44)	11.33 (2.06)

[a] Corsi visuo-spatial working memory task, (Corsi, 1972)
[b] Nepsy non-word repetition task (Korkman et al., 1998).
[c] Rapid serial naming (Denckla & Rudel, 1974; values from the Finnish standardization Ahonen et al., 2006).
* Significantly different from the control group ($p < .01$).
** Significantly different from the control group ($p < .05$).

Verbal working memory was measured using the repetition of nonsense words task from the Nepsy battery (Korkman, Kirk, & Kemp, 1998). This test involves the immediate repetition of auditorily presented nonwords and thus requires temporary storage of unfamiliar phonological sequences. Thus it is described as an index of phonological short-term memory (Gathercole, Willis, Baddeley, & Emslie, 1994). The task contains 15 nonwords in an increasing order of length and difficulty. Credit was given for each correct repetition, with immediate self-corrections credited as a correct response. Korkman reported the Cronbach Alpha of the Finnish version of the task to be .71 (Korkman, 2000).

The nonword repetition task correlates with WISC-III digit span (.50 in the US normative sample data, Korkman et al., 1998) and sentence repetition tasks of Nepsy (.39, Korkman, 2000), suggesting that these working memory tasks tap a mixture of common and distinct abilities (Gathercole, Willis, Emslie, & Baddeley, 1992).

Visuo-spatial working memory was assessed with the Corsi blocks task (Corsi, 1972; described by Milner, 1971). The apparatus for this task is a set of identical blocks glued to random positions on a board. On each trial the participant observes the experimenter tap a sequence of blocks and then attempts to reproduce the sequence. Span is measured by gradually increasing sequence length to find the point at which performance breaks down.

We used the original arrangement of the blocks (Berch, Krikorian, & Huha, 1998; Farrell Pagulayan, Busch, Medina, Bartok, & Krikorian, 2006). The apparatus consisted of nine 4.4-cm square wooden blocks. To aid the experimenter, the numbers 1–9 were painted on the side of each block facing away from the child. Blocks were tapped at a rate of one per second and no block was tapped more than once in a trial. Two trials of the same sequence of length were presented. If either one was repeated correctly, a sequence with one more block was tapped. This incremental procedure was continued to determine span—the longest sequence correctly repeated before two successive failures.

Span limit as measured by the Corsi task has been shown to be an index of the capacity of the visuospatial sketch pad (Vandierendonck et al., 2004), dissociated from verbal serial recall (Alloway, Gathercole, & Pickering, 2006). The visuo-spatial span has been shown to predict children's numerical development (Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003; Kyttälä & Lehto, 2008).

3.4. Control measure

To control whether the possible improvement in children's performance would generalize to a skill not trained at all in the intervention, we used Rapid serial naming task (RSN, Denckla & Rudel, 1974; standardized Finnish version by Ahonen, Tuovinen, & Leppäsaari, 2006) as a repeated control measure. This task involves 50 colored blocks (black, red, yellow, green and blue) arranged in rows of ten in a random order. The child is instructed to name all the colors as fast as possible. The total time is used as a measure. The RSN task was selected because it has been shown to be fairly resistant to spontaneous improvement and has high test–retest reliability (Ahonen et al., 2006). Test–retest reliability for the two pre-assessments in this study was .87.

3.5. Measures of number skills

We used four tasks to assess number skills: number comparison, verbal counting, object counting (divided into subitizing and counting), and arithmetic.

3.5.1. Verbal counting

The task contained three counting subtasks. Counting forward from 1 to 24, counting backwards from 12 to 1 and counting even numbers from 2 to 24. For each subtest the child was assigned up to 24 points, one from each correct step in the sequence in the first task and two points in the latter two tasks. A sum score for counting skill was determined by summing the scores of these three subtests (maximum of 72 points). The Cronbach's Alpha calculated from the first assessment was .80, and test–retest reliability was .85.

3.5.2. Object counting

Random patterns of dots from 1 to 6 were presented on a computer screen. The child was asked to say aloud the number of dots as fast as possible. Because small children have difficulties in counting silently, a voice trigger was not used. Instead, a trained assistant pressed the mouse button at the same time as the child said the answer. This test consisted of 4 practice items and 18 test items, three for each number of dots.

Response latencies for the dot counting task have been found to produce two different linear relations. First, there is a fast and accurate subitizing process with almost a flat increase in reaction time (Piazza, Mechelli, Butterworth, & Price, 2002). Second, there is a slow and attention-demanding counting process. On average, children of preschool age have been found to be able to subitize up to three objects (Hannula, Räsänen, & Lehtinen, 2007). After three items children have to rely on counting. Typically a linear increase in naming time is found for 4–9 dots and reflects the speed of a counting (Svenson & Sjöberg, 1978).

Of a total of 4302 responses only 4% were incorrect. Because of this small number of incorrect responses, they were not analyzed further, and only results from reaction times calculated from correct responses are presented. Two scores were calculated from the correct answers. First, we calculated the mean of the median reaction times for 1–3 dots (subitizing range). Second, we calculated an estimate for the average counting time per item to 4–6 dots (counting range). The latter value was calculated by dividing the median reaction times of the correct answers with the number of dots in each stimulus. The test–retest reliabilities for subitizing and object counting were .87 and .77, respectively.

3.5.3. Number comparison

Children were presented two Arabic numbers from one to nine horizontally. The child was asked to choose the larger one of them. The child held the mouse, left thumb on the left button and right thumb on the right one, and was instructed to press as fast as possible a button, which was on the same side as the bigger number. All combinations of even-number pairs were presented in a random order as well as pairs 1 vs. 2 and 8 vs. 9, to avoid the effect of extreme values. The items with 1 or 9 were excluded from the analysis. The score was the mean of the median reaction time. Because only 10% of answers were incorrect, there were no differences in error amounts between groups or assessments, and only reaction times were analyzed. Test–retest reliability of the reaction time measure was .87.

3.5.4. Arithmetic

Arithmetical skills were assessed by means of a three-minute paper-and- pencil test (Aunola & Räsänen, 2007) consisting of simple addition and subtraction problems. The child was allowed to answer either by writing the number or by saying the answer aloud. If a child was unable to solve any calculation tasks with written numbers, an additional task with three items was given. The child was asked to calculate the number of objects (circles and squares) from pictures and to add corresponding number symbols next to each of three pictures. The score was the total number of correct answers. Test–retest reliability for this task was .86.

3.6. Procedure

The procedure consisted of two pre-assessments conducted during one week, a three-week intervention and two post-assessments, one conducted immediately after the end of the intervention and a delayed assessment three weeks later. Each assessment took between 20 and 30 min. The second author and a trained research assistant conducted a portion of each of the assessments. In the preschools there was organized a quiet separate room for the assessments.

The first pre-assessment included three cognitive and four numerical tasks presented in the following order: Corsi Blocks, Non-Words Repetition, Dot counting (computerized test), Number comparison (computerized test), Verbal Counting, Arithmetic and Rapid Serial Naming of colors. The second pre-assessment and the post-assessments included four numerical tasks and the control task (RSN), presented in the same order.

Following the pre-assessments the preschool teachers were instructed to conduct a 10–15-min play session daily for three weeks. Teachers were asked to observe the playing time as well as the motivation for playing. Teachers were provided with forms to record start and ending times and children's reactions. The control group did not participate in these sessions.

4. Results

The results section is divided into three parts. First we compared the effectiveness of the intervention in the intervention groups to the control group with multivariate analysis of variance (ANOVA). Because there were pre-treatment differences due to the selection procedure of the groups, gain scores were used in comparisons instead of pre- and post-assessment values (McGaw & Glass, 1980). Second we carried out an analysis of the variables for which the intervention groups made significant progress. Last, we calculated effect sizes for all numerical tasks in a similar fashion to that done in previous controlled studies.

4.1. Group comparisons at pre-assessment

Results from pre-assessments were congruent with teachers' evaluations. The experimental groups were clearly poorer in all number skills compared to the randomly selected control group: Verbal counting, $F(2,56) = 8.266$, $p = .001$, subitizing 1-3 objects, $F(2,56) = 5.624$, $p = .006$, object counting speed of 4–6 objects, $F(2,56) = 5.213$, $p = .008$, number comparison, $F(2,56) = 5.626$, $p = .006$, and arithmetic $F(2,56) = 9.758$, $p < .001$. On average children in the intervention groups were close to one standard deviation poorer in numerical tasks than children in the control group. Post hoc tests revealed that intervention groups (NR and GG-M) did not differ from each other (all $p > .05$) in the pre-assessment. Means and standard deviations are presented in Table 3.

Both intervention groups showed lower performance in visuo-spatial working memory, $F(2,56) = 5.163$, $p = .009$, and in Rapid Serial Naming task, $F(2,56) = 4.739$, $p = .013$, than the control group. Post hoc tests revealed that the experimental groups did not differ from each other (all $p > .05$). There was no differences between the groups in verbal working memory, $F(2,56) = 2.242$, $p = .116$. The means and standard deviations of working memory and RSN tasks are presented in Table 2.

4.2. Comparison of intervention and control groups

A series of ANOVAs were performed to analyze differences in gain scores in the numerical tasks and in the non-numerical control task (RSN). In the initial analyzes we used the working memory and gain in the non-numerical control task measures as covariates, but because they did not make a significant contribution to the results, the further analyses were done without covariates.

We first compared the improvement of performance from pre-assessment to the immediate post-intervention. There was a significant difference in the number comparison task, $F(2,56) = 3.658$,

Table 3
Means and standard deviations in the repeated measures for pre-, post-, and delayed post-assessments.

	Groups								
	Control			GraphoGame-M			NumberRace		
	pre	post	delayed	pre	post	delayed	pre	post	delayed
Verbal Counting (points)	63.02	67.93	66.55	45.40	53.20	54.33	51.17	53.47	59.13
SD	10.87	8.69	9.71	19.36	19.02	17.37	14.95	15.74	19.10
Number comparison (ms)	1042	994	947	1307	1101	1052	1351	1185	1131
SD	262	257	268	362	274	199	412	360	297
Subitizing (object counting 1–3 items) (ms)	1284	1226	1182	1357	1291	1322	1499	1379	1340
SD	202	233	225	171	286	247	222	266	203
Object counting (4–6 items) (ms)	587	529	532	670	606	644	730	698	677
SD	132	109	116	123	104	103	141	162	168
Arithmetic (points)	6.57	7.31	7.90	4.73	5.27	5.67	4.70	5.80	5.00
SD	1.77	2.56	2.86	1.68	1.98	2.09	1.13	0.94	1.25
Rapid Serial naming (standard score)	0.47	0.43	0.41	-0.14	0.04	0.08	-0.21	-0.16	-0.13
SD	0.70	0.71	0.85	0.79	0.78	0.55	0.98	0.87	1.16

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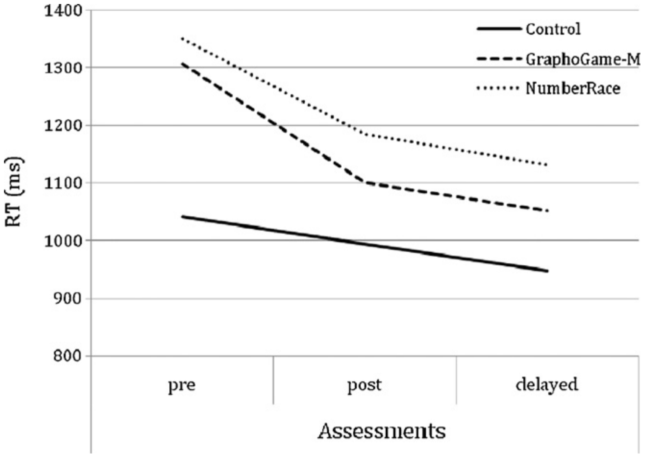

Fig. 1. Mean reaction times (ms) in the number comparison task in pre-, post- and delayed post-assessments.

$p = .032$. Post hoc comparisons revealed that the GG-M group ($M = 206$ ms, $SD = 149$) had improved more than the control group ($M = 47$ ms, $SD = 146$), ($p = .016$). Similarly the NR group ($M = 166$ ms, $SD = 311$) also showed more improvement than the control group, but this result is not statistically significant ($p = .069$). The experimental groups did not differ from each other ($p = .585$). There were no differences in gains in other numerical tasks (all $p > .324$) or in the non-numerical control (RSN) task, $F(2,56) = .734$, $p = .484$.

Second, we compared gain scores from the pre-assessment to the delayed post-assessment. The main result was the same. There remained a significant difference in the number comparison task, $F(2,56) = 3.661$, $p = .032$. Post hoc comparisons revealed that the GG-M group ($M = 256$ ms, $SD = 221$) had improved more than the control group ($M = 94$, $SD = 192$, $p = .016$). Similarly the NR group ($M = 219$ ms, $SD = 218$) showed more improvement than the control group, but this result was not statistically significant ($p = .061$). The experimental groups did not differ from each other ($p = .638$). Again there were no differences in gains in other numerical tasks (all $p > .079$) or in the non-numerical control task, $F(2,56) = 1.080$, $p = .347$.

4.3. Differences in number comparison performance between intervention groups

Although the intervention groups did not differ from each other on average in speed of responding or in improving performance in the number comparison task, items in the number comparison tasks are not equal. It is a different thing to compare 2–8 and 4–6. It has been found that the smaller the difference between the numbers to be compared, the more time is needed to make a comparative judgment, i.e., the distance effect noted earlier. We thus broke down the reaction times to see whether the groups differed from each other in different types of items.

We included only differences of two (small, e.g. 2 vs. 4, 4 vs. 6), four (intermediate, 2 vs. 6) and six (large, 2 vs. 8). To analyse whether we could find the distance effect among this age group, we conducted a 3 × 3 × 3 (Assessment × Distance × Group) repeated measures ANOVA. We found significant main effects for Assessment, $F(2,108) = 31.932$, $p < .001$, Distance, $F(2,108) = 31.932$, $p < .001$, and Group, $F(2,54) = 5.600$, $p = .006$. An assessment-group interaction approached significance, $F(4,108) = 2.169$, $p < .077$.

Results indicate that all children improved their performance from one assessment to another and that the control children outperformed the intervention groups (see Table 3 for means and standard deviations). The interaction effect comes from the fact that the intervention groups approached the control group in their performance from pre- to post-assessment (see Fig. 1). We also found a typical distance effect: As the difference between the numbers increased, the easier the comparison process

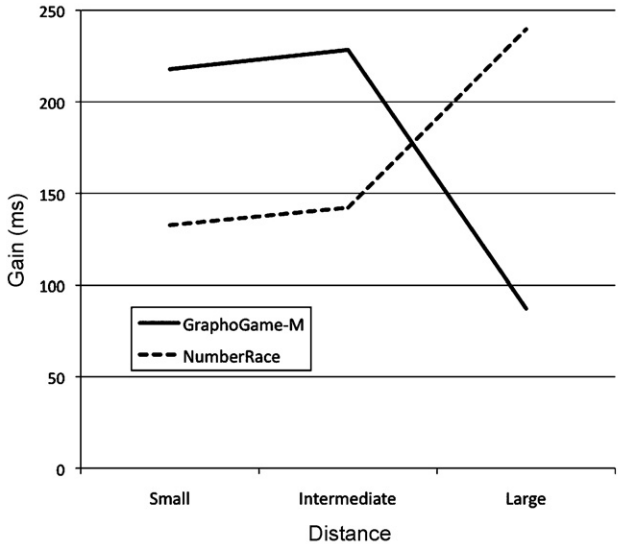

Fig. 2. Average gain from pre- to post-assessment in the number comparison task as a function of small, intermediate and large differences (distance) between the number pairs in the two intervention groups.

was. The mean reaction times were 1190 (SE = 39), 1111 (SE = 39) and 1049 ms (SE = 37) for small, intermediate and large distances, respectively.

Of interest was the interaction between the distance effect and the improvement in the intervention groups. To see whether these groups differed from each other in their level of improvement in the number comparison task, a 3 × 2 (Distance × Group) repeated measures ANOVA was performed on the gain scores in the number comparison task. We found a distance–group interaction, $F(2,56) = 3.134$, $p = .051$ (Sphericity assumed). Post hoc t-tests showed that the NR group showed significantly more improvement in items with large difference, $t(28) = 1.979$, $p = .031$, one-tailed (equal variance not assumed), but the groups did not differ in how much they improved in small or intermediate comparisons ($p > .212$). The interaction is illustrated in Fig. 2.

This effect was, however, short-lived. When conducting the same analysis using the gain scores from pre-assessment to delayed post-assessment, the interaction effect disappeared, $F(2,54) = .255$, $p = .776$. The gain scores from pre to the delayed post-assessment for the GG-M group were 193 ms (SD = 230), 320 ms (SD = 466), and 263 ms (SD = 253), and for the NR group 240 ms (SD = 254), 161 ms (SD = 474), and 256 ms (SD = 478) for small, intermediate and large differences, respectively.

4.4. *Effect sizes*

In meta-analyses effect sizes are used to compare studies to each other. In our introduction we had calculated the effect sizes from intervention studies on early number skills. For comparative purposes we provide the same statistics from our own data in Table 4. The average effect sizes in our study varied similarly as in previous studies. Even in the task affording the strongest impression (ES average .45) that our CAI games would help children to learn, the number comparison task, the confidence interval of the effect size ranges from non-significant −.18 to large 1.08, comparable to the other studies on CAI interventions of early number skill (see Table 1).

5. Discussion

We introduced two different types of computerized intervention games in a short intensive intervention to improve early number skills in low-achieving children. Low achievement in early number

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Table 4
Effect sizes (Hedges correction) and confidence intervals for effect sizes calculated from gains of control and intervention groups.

Groups	Assessment	Task	Effect Size	Confidence Interval for Effect Size	
				Lower	Upper
GG-M vs. Control	Pre–post	Verbal counting	.20	−.43	.82
		Number Comparison	.52	−.11	1.15
		Subitizing	.32	−.30	.95
		Object counting	.01	−.61	.64
		Arithmetic	−.12	−.74	.51
GG-M vs. Control	Pre–delayed post	Verbal counting	.37	−.26	1.00
		Number Comparison	.53	−.10	1.16
		Subitizing	−.02	−.64	.60
		Object counting	−.22	−.85	.40
		Arithmetic	−.22	−.85	.40
NR vs. Control	Pre–post	Verbal counting	−.21	−.83	.42
		Number Comparison	.36	−.26	.99
		Subitizing	.29	−.34	.92
		Object counting	−.19	−.82	.43
		Arithmetic	.22	−.40	.85
NR vs. Control	Pre–delayed post	Verbal counting	.35	−.28	.98
		Number Comparison	.38	−.24	1.01
		Subitizing	.24	−.39	.86
		Object counting	−.02	−.64	.60
		Arithmetic	−.64	−1.27	.00
Average			.44	−.19	1.07

Note. GG-M = Graphogame-M group. NR = Numberrace group. Pre-post = Gain in post-assessment minus gain in pre-assessment. Pre-delayed post = Gain in delayed post-assessment minus gain in pre-assessment.

skills, according to current neuropsychological research, is connected to very basic numerical processes shared by humans and animals. How these early processes are connected to later developing cultural number skills, and how education changes processing of numerical information, are still open questions.

Two main approaches to the question of the development of early number skills have been proposed. One approach stresses importance of the sense of approximate magnitudes as a vital aspect of individual differences in basic number processes (Dehaene, 2009), while the other emphasizes the role of constructing concepts of the small set of numerosities in learning the number system (Butterworth, 2005). We used these two approaches as heuristics in selecting the computer games for our intervention. The key difference between the two games selected lies in how they approach the numerical difference in number comparison. The Number Race (NR) game starts from a comparison of random dot patterns with large numerical difference, and the solution process does not require any verbal mediation. When the child shows progress, the game starts to produce harder items with smaller numerical differences between the numbers. The same is repeated with number symbols. The second game, the Graphogame-Math (GG-M), starts with small sets of organized dot patters, close to each other in numerical value. With repeated practice the game tries to teach the child the correspondences between the verbal labels (number words) and the quantities the labels represent. The comparison process in this task comes from the distractors, which are numerically close to the correct target. The child is constantly required to compare the quantities with small differences to find the correct response. When the child progresses, the game starts to produce harder items involving larger quantities, but the correct response continues to be numerically close to the distractors. The same process is repeated with number symbols.

Children were required to make comparisons between magnitudes and numbers in both games. Although the amount of training was short and daily practice lasted only 15 min or less, this exposure provided more repetition than is typically experienced in preschool. This exposure produced improved performance in a number comparison task.

The difference in what was compared in the two games affected the results. Children who were trained to compare small numerical differences (GG-M group) seemed to be more attuned to these differences, and they also showed improved performance on those items of the number comparison task on which the numerical difference was small. By contrast, children in the NR group were led to approach the number comparison differently. The game starts from large differences between the randomly placed dot patterns, and from large differences between numbers. The idea of the game is to prompt children to use the endogenous approximate number system. Short training of this type produced a significant gain in number comparison especially in items with larger differences between the numbers.

This short-lived effect requires more research. It may be that the result only reflects a practice effect: The more children compare certain quantities, the faster they become with exactly those quantities. Unfortunately, this practice effect was not controlled in our study. Both games do collect individual log files containing the frequencies of each stimulus and a child's response. However, the NR game always had only two numbers to be compared, and the version of the GG-M used in this study allowed having more than two targets at the same time, making it difficult to precisely produce comparable statistics of the frequencies. Technically this is easy to control in future studies.

Although the frequency of training certain number pairs could partly explain the differences in how children improved in the number comparison task, children in both groups still showed the typical distance effect. An alternative account is that the training taught children to approach the comparison task slightly differently. The children had not yet had exposure in school to Arabic number symbols. It may be that playing the GG-M game attuned children to concentrate on exact symbolic representations when confronting number symbols, while playing the NR game, which adapts on the basis of numerical difference, allowed children to concentrate on relative differences.

Similarly, Verguts and Fias (2004) exposed a nonsupervised neural network either to numerosity alone or numerosity paired with a symbol. The tuning curves were much narrower when symbolic inputs were provided, allowing more detailed discrimination between quantities, and thus faster responses with fewer errors to smaller numerical differences. Thus, the network developed different types of representations to symbolic and non-symbolic stimuli. Neural network models could also be used to simulate this kind of learning process with a restricted set of numbers and magnitudes. An interesting question is that of how different types of training might affect the learning speed of the magnitude representations to number symbols.

Although this interpretation is speculative, it illustrates the power of computer-assisted interventions. Using computer software, it is possible to present very tightly controlled stimuli in an entertaining game-like format that provides enough repetitions for learning. The recent discoveries of the key role of the basic magnitude representations in mathematical learning and behind mathematical learning disabilities (Piazza et al., submitted for publication) stress the importance of these kinds of focused intervention studies to elucidate the mechanisms involved in learning the symbolic number system.

We were successful in producing significant improvement in number comparison. However, our other expectations of improved performance in children with weak early number skills were not realized. Wilson, Dehaene, et al. (2006) found that five weeks training with the NR game improved subitizing, number comparison and subtraction. However, their study did not contain a control group, so the results of improvement were only suggestive. In the Wilson et al. study children's speed of responding in the subitizing task improved on average 300 ms. In our study, younger children with three weeks training improved their performance in a similar subitizing tasks on average 120 ms. This improvement was more than double, compared to the improvement of the non-playing control group (58 ms) or to the group playing another game (66 ms). However, individual variation within the groups was much larger than the average gain, reminding us that we need to be very careful when making interpretations based on results from a single intervention group without any control group.

Contrary to our expectations, there was no significant improvement in the counting tasks. In the GG-M game children are given a verbal label, and they are asked to find the corresponding quantity. In the object counting task, the process is reversed: The child is shown a certain number of objects and is required to produce the corresponding verbal label. In the NR game, when a child clicks a square in a boardgame-like path, the computer moves a piece and the game produces the counting sequence. This kind of passive training appears not to produce sufficient learning to produce an intervention effect. It is most probable that training counting requires explicit practice in producing the counting sequence or at least the target number word. Another open question is whether training would produce better results if actual vocalization were used.

The vocalization possibility offers new opportunities to CAI developers. Voice recognition technologies exist but have not been used in CAI studies. One of the biggest obstacles in using voice recognition is the limited capacity of computers to understand spoken language. The fact that the size of the number word vocabulary is very small and unequivocal compared to almost any other category of words offers a golden opportunity to study the roles of verbal production and vocalization in learning.

Our control group was passive, i.e., children did not get any attention beyond the assessments. The positive effects of extra attention are well known (the Hawthorne effect). The best option would be to use similar kind of activities with different contents (Fuchs & Fuchs, 2002). Due to limited resources, we were not able to emply this option. Instead we used a non-numerical control task. If the intervention effect were due just to extra attention or extra activities, there would be a similar improvement in tasks for which no training was provided. There was no significant training effect in the control task, and, furthermore, the gain in the control task did not contribute to the group differences when it was added as a covariate in the analysis of variance.

Another reason we used a group of typically performing children as a passive control group in our study is that it provided a unit of measure for our experimental tasks, providing us an estimate how much improvement in performance just repeating the same tasks would produce in a sample of same-aged children.

The disadvantage of having typically performing children as a control group to a group of low-performing children is the large difference in the starting level. There were also significant differences in the general cognitive skills between the groups, ones that have been connected to mathematical development (Kyttälä et al., 2009). There are two main alternatives to statistically control these effects in intervention studies. The first is to use the starting level as a covariate when analyzing the group differences. The second is to use gain scores. We used gain scores and the cognitive skills measured at the beginning of the study as covariates. The covariates did not correlate with the gain scores. Thus we can be rather certain that the significant findings are due to training effects and not contaminated by the general differences between the groups.

We found significant intervention effects, although they were moderate. The average ES was .44 for both intervention groups in the number comparison task. Although the intervention effects were significant in the number comparison task, the confidence interval of the effect sizes extended from negative to strong positive. These figures are close to those that have been found in meta-analytic studies since the 1960s. Most of the studies published do not present non-significant findings. In our study, 16 of 20 effect sizes were non-significant when we contrasted the gain in the intervention group to the improvement of the higher performing control group.

Computer-assisted learning has not met its expectations. However, personal computers and other electronic devices are a common feature of children's lives. As more and more computer applications continue to be developed to entertain and assist in learning, educational research has not kept up with this rapid change in how children interact with information. The database of controlled studies is limited and does not allow us to draw strong conclusions.

More than 25 years ago Clark (1983) raised the question of whether the medium itself had any effect on learning. In today's technologically oriented world this question may be irrelevant. The question should be revised to one of how media can be designed to improve learning, as well as to better understand the mechanisms of learning. The present study shows that even within a very limited content area and very short training time, very specific intervention effects can be identified. Our knowledge of the developing brain has increased dramatically with the help of new imaging technologies. Computer-assisted interventions can help us to learn how the brain learns.

References

Ahonen, T., Tuovinen, S., & Leppäsaari, T. (2006). *Nopean sarjallisen nimeämisen testi*. Jyväskylä: Niilo Mäki –instituutti.

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child Development*, *77*(6), 1698–1716.

Andersson, U., & Lyxell, B. (2007). Working memory deficit in children with mathematical difficulties: A general or specific deficit? *Journal of Experimental Child Psychology*, *96*, 197–228.

Ansari, D. (2008). Effects of development and enculturation on number representation in the brain. *Nature Reviews. Neuroscience*, *9*(4), 278–291.

Ansari, D., Garcia, N., Lucas, E., Hamon, K., & Dhital, B. (2005). Neural correlates of symbolic number processing in children and adults. *Neuroreport*, *16*(16), 1769–1773.

Anselmo, S., & Zinck, R. (1987). Computers for young children? Perhaps. *Young Children*, 22–27.

Aubrey, C., & Godfrey, R. (2003). The Development Of Children's Early Numeracy Through Key Stage 1. *British Educational Research Journal*, *29*(6), 821–840.

Aubrey, C., Dahl, S., & Godfrey, R. (2006). Early mathematics development and later achievement: Further evidence. *Mathematics Education Research Journal*, *18*(1), 27–46.

Aunola, K., Leskinen, E., Lerkkanen, M.-K., & Nurmi, J.-E. (2004). Developmental dynamics of math performance from preschool to grade 2. *Journal of Educational Psychology*, *96*(4), 699–713.

Aunola, K., & Räsänen, P. (2007). *The 3-minutes Basic Arithmetic Test*. Unpublished.

Azevedo, R., & Bernard, R. (1995). Assessing the eects of feedback in computer-assisted learning. *British Journal of Educational Technology*, *26*(1), 57–58.

Baxter, J. A., Woodward, J., & Olson, D. (2001). Effects of reform-based mathematics instruction in five third grade classrooms. *Elementary School Journal*, *101*(5), 529–548.

Benjamin, L. T. (1988). A history of teaching machines. *American Psychologist*, *43*(9), 703–712.

Berch, D. B. (2005). Making sense of number sense: Implications for children with mathematical disabilities. *Journal of Learning Disabilities*, *38*(4), 333–339.

Berch, D. B., Krikorian, R., & Huha, E. M. (1998). The Corsi block-tapping task: methodological and theoretical considerations. *Brain and Cognition*, *38*(3), 317–338.

Booth, R. D. L., & Thomas, M. O. J. (2000). Visualization in mathematics learning: Arithmetic problem-solving and student difficulties. *Journal of Mathematical Behavior*, *18*(2), 169–190.

Brown, D. L., & Presmeg, N. C. (1993). Types of imagery used by elementary and secondary school students in mathematical reasoning. In *Paper presented at the Proceedings of the 17th Annual Meeting of the International Group for the Psychology of Mathematics Education* Tsukuba, Japan,

Buckleitner, W. W., & Hohmann, C. F. (1987). Technological priorities in the education of young children. *Childhood Education*, *63*, 337–340.

Bull, R., Johnston, R. S., & Roy, J. A. (1999). Exploring the roles of the visuo-spatial sketch pad and central executive in children's arithmetical skills: Views from cognition and developmental neuropsychology. *Developmental Neuropsychology*, *15*(3), 421–442.

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: inhibition, switching and working memory. *Developmental Neuropsychology*, *19*(3), 273–293.

Burns, P. (1981). A quantitative synthesis of research findings relative to the pedagogical effectiveness of computer- assisted instruction in elementary and secondary schools. *Dissertation Abstracts International*, *42*, 2946A.

Butterworth, B. (1999). *The Mathematical Brain*. Macmillan.

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry*, *46*(1), 3–18.

Cantlon, J. F., & Brannon, E. M. (2005). Semantic congruity affects numerical judgments similarly in monkeys and humans. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(45), 16507–16511.

Cantlon, J. F., & Brannon, E. M. (2006). Shared system for ordering small and large numbers in monkeys and humans. *Psychological Science: A Journal of the American Psychological Society/APS*, *17*(5), 401–406.

Cantlon, J. F., Brannon, E. M., Carter, E. J., & Pelphrey, K. A. (2006). Functional imaging of numerical processing in adults and 4-y-old children. *PLoS Biology*, *4*(5), e125.

Carey, S. (2004). *On the origin of concepts*. Daedulus.

Cawley, J., Parmar, R., Foley, T. E., Salmon, S., & Roy, S. (2001). Arithmetic performance of students: Implications for standards and programming. *Exceptional Children*, *67*(3), 311–328.

Cawley, J., Parmar, R., Yan, W., & Miller, J. H. (1998). Arithmetic computation performance of students with special needs: Implications for curriculum. *Special Needs Research & Practice*, *13*(2), 68–74.

Chard, D., Clarke, B., Baker, S., Otterstedt, J., Braun, D., & Katz, R. (2005). Using measures of number sense to screen for difficulties in mathematics: Preliminary findings. *Assessment for Effective Intervention*, *30*, 3–14.

Christakis, D. A., Ebel, B. E., Rivara, F. P., & Zimmerman, F. J. (2004). Television, video, and computer game usage in children under 11 years of age. *The Journal of Pediatrics*, *145*(5), 652–656.

Christensen, C. A., & Gerber, M. M. (1990). Effectiveness of computerized drill and practice games in teaching basic math facts. *Exceptionality*, *1*, 149–165.

Clark, R. E. (1983). Reconsidering research on learning from media. *Review of Educational Research*, *53*(4), 445–459.

Clarke, B., & Shinn, M. (2004). A preliminary investigation into the identification and development of early mathematics curriculum-based measurement. *School Psychology Review*, *33*, 234–248.

Clements, D. H. (1986). Effects of logo and CAI environments on cognition and creativity. *Journal of Educational Psychology*, *78*(4), 309–318.

Clements, D. H. (1994). The uniqueness of the computer as a learning tool: insights from research and practice. In J. L. Wright, & D. D. Shade (Eds.), *Young children: Active learners in a technological age* (pp. 31–49). Washington, DC: National Association for the Education of Young Children.

Clements, D. H., & Gullo, D. F. (1984). Effects of computer programming on young children's cognition. *Journal of Educational Psychology*, *76*, 1051–1058.
Clements, D. H., & Nastasi, B. K. (1993). Electronic media and early childhood education. In B. Spodek (Ed.), *Handbook of Research on the Education of Young Children* (pp. 251–275). New York: Macmillan.
Claessens, A., Duncan, G., & Engel, M. (2009). Kindergarten skills and fifth-grade achievement: Evidence from the ECLS-K. *Economics of Education Review*, *28*(4), 415–427.
Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Earlbaum Associates.
Cohen Kadosh, R., Lammertyn, J., & Izard, V. (2008). Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. *Progress in Neurobiology*, *84*(2), 132–147.
Conway, A. R., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences*, *7*(12), 547–552.
Corsi, P.M. (1972). Human memory and the medial temporal region of the brain. Unpublished doctoral dissertation. Montreal, Canada: McGill University.
Cumming, J. J., & Elkins, J. (1999). Lack of automaticity in the basic addition facts as a characteristic of arithmetic learning problems and instructional needs. *Mathematical Cognition*, *5*(2), 149–180.
Dehaene, S. (2009). Origins of mathematical intuitions: The case of arithmetic. *Annals of the New York Academy of Sciences*, *1156*, 232–259.
Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology*, *20*(3–6), 487–506.
Dempsey, J. V., Rasmussen, K., & Lucassen, B. (1996). Instructional gaming: Implications for instructional technology. In *Paper presented at the Annual Meeting of the Association for Educational Communications and Technology* Nashville, TN.
Denckla, M. B., & Rudel, R. (1974). Rapid "Automatized" naming of pictured objects, colors, letters and numbers by normal children. *Cortex*, *10*(2), 186–202.
De Smedt, B., Verschaffel, L., & Ghesquiere, P. (2009). The predictive value of numerical magnitude comparison for individual differences in mathematics achievement. *Journal of Experimental Child Psychology*, *103*(4), 469–479.
Desoete, A., & Grégoire, J. (2006). Numerical competence in young children and in children with mathematics learning disabilities. *Learning and Individual Differences*, *16*, 351–367.
Desoete, A., Ceullemans, A., Royers, H., & Huylebroek, A. (2009). Subitizing or counting as possible screening variables for learning disabilities in mathematics education or learning? *Educational Research Review*, *4*, 55–66.
Diester, I., & Nieder, A. (2007). Semantic associations between signs and numerical categories in the prefrontal cortex. *PLoS Biology*, *5*(11), e294.
Din, F., & Calao, J. (2001). The eects of playing educational video games on kindergarten achievement. *Child Study Journal*, *31*(2), 95–102.
Donlan, C., Cowan, R., Newton, E., & Lloyd, D. (2007). The role of language in mathematical development: evidence from children with specific language impairments. *Cognition*, *103*, 23–33.
Dowker, A. (2005). *Individual differences in arithmetic. Implications for psychology, neuroscience and education*. Hove, UK: Psychology Press.
Dowker, A. (2008). Individual differences in numerical abilities in preschoolers. *Developmental Science*, *11*, 650–654.
Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., et al. (2007). School readiness and later achievement. *Developmental Psychology*, *43*(6), 1428–1446.
Elliot, A., & Hall, N. (1997). The impact of self-regulatory teaching strategies on "at-risk" preschoolers' mathematical learning in a computer mediated environment. *Journal of Computing in Childhood Education*, *8*, 187–198.
Farrell Pagulayan, K., Busch, R. M., Medina, K. L., Bartok, J. A., & Krikorian, R. (2006). Developmental normative data for the corsi block-tapping task. *Journal of Clinical and Experimental Neuropsychology*, *28*(6), 1043–1052.
Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number core systems of number. *Trends in Cognitive Sciences*, *8*(7), 307–314.
Fitz-Gibbon, C. T. (1985). The implications of meta-analysis for educational research. *British Educational Research Journal*, *11*(1), 45–49.
Fletcher-Flinn, C. M., & Gravatt, B. (1995). The ecacy of computer assisted instruction (CAI): A meta-analysis. *Journal of Educational and Computing Research*, *12*, 219–242.
Fuchs, L. S., & Fuchs, D. (2002). Mathematical problem-solving profiles of students with mathematics disabilities with and without comorbid reading disabilities. *Journal of Special Needs*, *35*(6), 564–574.
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 combination skill in at-risk first graders. *Journal of Learning Disabilities*, *39*(5), 467–475.
Gathercole, S. E., Willis, C. S., Baddeley, A. D., & Emslie, H. (1994). The children's test of nonword repetition: A test of phonological working memory. *Memory*, *2*, 103–127.
Gathercole, S. E., Willis, C. S., Emslie, H., & Baddeley, A. (1992). Phonological memory and vocabulary development in the early school years: A longitudinal study. *Developmental Psychology*, *28*, 887–898.
Geary, D. C. (1995). Reflections of evolution and culture in children's cognition: Implications for mathematical development and instruction. *American Psychologist*, *50*(1), 24–27.
Geary, D. C. (2004). Mathematics and learning disabilities. *Journal of Learning Disabilities*, *37*(1), 4–15.
Geary, D. C., Hoard, M. K., Byrd-Craven, J., & DeSoto, M. C. (2004). Strategy choices in simple and complex addition: Contributions of working memory and counting knowledge for children with mathematical disability. *Journal of Experimental Child Psychology*, *88*(2), 121–151.
Geary, D. C., Hamson, C. O., & Hoard, M. K. (2000). Numerical and arithmetical cognition: A longitudinal study of process and concept deficits in children with learning disability. *Journal of Experimental Child Psychology*, *77*, 236–263.
Gelman, R., & Gallistel, C. R. (1978). *The child's understanding of number*. Cambridge, MA: Harvard University Press.
Gelman, R., & Butterworth, B. (2005). Number and language: how are they related? *Trends in Cognitive Sciences*, *9*(1), 6–10.

Gersten, R., Jordan, N. C., & Flojo, J. R. (2005). Early identification and interventions for students with mathematics difficulties. *Journal of Learning Disabilities*, *38*(4), 293–304.

Glass, G. V., McGaw, B., & Smith, M. L. (1981). *Meta-analysis in social research*. Beverly Hills, CA: Sage.

Goodwin, L. D., Goodwin, W. L., & Garel, M. B. (1986). Use of microcomputers with preschoolers: A review of the literature. *Early Childhood Research Quarterly*, *1*, 269–286.

Goodwin, L. D., Goodwin, W. L., Nansel, A., & Helm, C. P. (1986). Cognitive and affective effects of various types of microcomputer use by preschoolers. *American Educational Research Journal*, *23*, 348–356.

Grover, S. C. (1986). A field of the use of cognitive-developmental principles in microcomputer design for young children. *Journal of Educational Research*, *79*, 325–332.

Hanich, L. B., Jordan, N. C., Kaplan, D., & Dick, J. (2001). Performance across different areas of mathematical cognition in children with learning difficulties. *Journal of Educational Psychology*, *93*(3), 615–626.

Hannula, M., Räsänen, P., & Lehtinen, E. (2007). Development of counting skills: Contributions from tendency to focus on numerosity and subitizing. *Mathematical Teaching and Learning*, *9*(1), 51–57.

Halberda, J., Mazzocco, M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature*, *455*(7213), 665–668.

Hartley, S. (1978). Meta-analysis of the eects of individually paced instruction in mathematics. *Dissertation Abstracts International*, *38*(7-A), 4003.

Hasselbring, T. S., Goin, L. I., & Bransford, J. D. (1988). Developing math automaticity in learning handicapped children: The role of computerized drill and practice. *Focus on Exceptional Children*, *20*(6), 1–7.

Hayes, D. S., Chemelski, B. E., & Birnbaum, D. W. (1981). Young children's incidental and intentional re- tention of televised events. *Developmental Psychology*, *17*, 230–232.

Hedges, L. V., & Olkin, I. (1985). *Statistical methods for meta-analysis*. Orlando, FL: Academic Press.

Hegarty, M., & Kozhevnikov, M. (1999). Types of visual-spatial representations and mathematical problem solving. *Journal of Educational Psychology*, *91*(4), 684–689.

Hegerty, M., Mayer, R. E., & Monk, C. A. (1995). Comprehension of arithmetic word problems: A comparison of successful and unsuccessful problem solvers. *Journal of Educational Psychology*, *87*(1), 18–32.

Howard, J. R., Eatson, J. A., Brinkley, V. M., & Ingels-Young, G. (1994). Comprehension monitoring, stylistic differences, pre-math knowledge, and transfer: a comprehensive pre-math/spatial development computer-assisted instruction (CAI) and Logo curriculum designed to test their effects. *Journal of Educational Computer Research*, *11*, 91–105.

Hughes, M., & Macleod, H. (1986). Using LOGO with very young children. In R. W. Lawler (Ed.), *Cognition and computers: Studies in learning*. Chichester, NY: Ellis Horwood.

Hungate, H. (1982). Computers in the kindergarten. *The Computing Teacher*, *9*(5), 15–18.

Isaacs, E. B., Edmonds, C. J., Lucas, A., & Gadian, D. G. (2001). Calculation difficulties in children of very low birthweight: A neural correlate. *Brain: A Journal of Neurology*, *124*(9), 1701–1707.

Bogoshi, J., Naidoo, K., & Webb, J. (1987). The oldest mathematical artifact. *The Mathematical Gazette*, *71*, 294.

Janssen, R., De Boeck, P., Viaene, M., & Vallaeys, L. (1999). Simple mental addition in children with and without mild mental retardation. *Journal of Experimental Child Psychology*, *74*, 261–281.

Jordan, N. C., & Hanich, L. B. (2003). Characteristics of children with moderate mathematics deficiencies: A longitudinal perspective. *Special Needs Research & Practice*, *18*(4), 221–231.

Jordan, N. C., Hanich, L. B., & Kaplan, D. (2003). Arithmetic fact mastery in young children: A longitudinal investigation. *Journal of Experimental Child Psychology*, *85*(2), 103–119.

Jordan, N. C., Kaplan, D., Locuniak, M. N., & Ramineni, C. (2007). Predicting first-grade math achievement from developmental number sense trajectories. *Learning Disabilities Research and Practice*, *22*(1), 36–46.

Jordan, N. C., Kaplan, D., Nabors Olah, L., & Locuniak, M. N. (2006). Number sense growth in kindergarten: A longitudinal investigation of children at risk for mathematics difficulties. *Child Development*, *77*(1), 153–175.

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology*, *45*(3), 850–867.

Khalili, A., & Shashaani, L. (1994). The eectiveness of computer applications: a meta-analysis. *Journal of Research on Computing in Education*, *27*(1), 48–61.

Koontz, K. L., & Berch, D. B. (1996). Identifying simple numerical stimuli: Processing inefficiencies exhibited arithmetic learning disabled children. *Mathematical Cognition*, *2*, 1–23.

Koponen, T., Mononen, R., Rasanen, P., & Ahonen, T. (2006). Basic numeracy in children with specific language impairment: Heterogeneity and connections to language. *Journal of Speech, Language, and Hearing Research: JSLHR*, *49*(1), 58–73.

Korkman, M. (2000). *Nepsy. Käsikirja II*. Helsinki: Psykologien kustannus Oy.

Korkman, M., Kirk, U., & Kemp, S. (1998). *NEPSY. A developmental neuropsychological assessment manual*. San Antonio: The Psychological Corporation.

Kraus, W. H. (1981). Using a computer game to reinforce skills in addition basic facts in second grade. *Journal for Research in Mathematics Education*, *12*, 152–155.

Kroesbergen, E. H., & van Luit, J. E. H. (2003). Mathematics interventions for children with special educational needs: A meta-analysis. *Remedial and Special Education*, *24*(2), 97–114.

Kucian, K., Loenneker, T., Dietrich, T., Dosch, M., Martin, E., & von Aster, M. (2006). Impaired neural networks for approximate calculation in dyscalculic children: A functional MRI study. *Behavioral and Brain Functions*, *2*, 31.

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*. Hillsdale, NJ: LEA Publishers.

Kulik, C.-L., & Kulik, J. A. (1991). Effectiveness of computer-based instruction: An updated analysis. *Computers in Human Behavior*, *7*, 75–94.

Kyttälä, M. (2008). Visuospatial working memory in adolescents with poor performance in mathematics: variation depending on reading skills. *Educational Psychology*, *28*(3), 273–289.

Kyttälä, M., Aunio, P., & Hautamaki, J. (2009). Working memory resources in young children with mathematical difficulties. Scandinavian Journal of Psychology. doi:10.1111/j.1467-9450.2009.00736.x.

Kyttälä, M., Aunio, P., Lehto, J. E., Van Luit, J. E. H., & Hautamäki, J. (2003). Visuospatial working memory and early numeracy. *Educational and Child Psychology*, *20*, 65–76.

Kyttälä, M., & Lehto, J. (2008). Some factors underlying mathematical performance: The role of visuospatial working memory and non-verbal intelligence. *European Journal of Psychology of Education*, *XXII*(1), 77–94.

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8-9-year-old students. *Cognition*, *93*(2), 99–125.

Lavin, R., & Sanders, J. (1983). *Longitudinal evaluation of the C/A/I computer assisted instruction Title 1 Project: 1979–1982*. Chelmsford, MA: Merrimack Education Center.

Lemer, C., Dehaene, S., Spelke, E., & Cohen, L. (2003). Approximate quantities and exact number words: Dissociable systems. *Neuropsychologia*, *41*, 1942–1958.

Locuniak, M., & Jordan, N. (2008). Using Kindergarten Number Sense to Predict Calculation Fluency in Second Grade. *Journal of Learning Disabilities*, *41*(5), 451–459.

Lucangeli, D., Tressoldi, P. E., & Cendron, M. (1998). Cognitive and metacognitive abilities involved in the solution of mathematical word problems: Validation of a comprehensive model. *Contemporary Educational Psychology*, *23*(3), 257–275.

Malofeeva, E. (2005). *Meta-analysis of mathematics instruction with young children*. Unpublished Dissertation, University of Notre Dame, Notre Dame, IN.

McCollister, T. S., Burts, D. C., Wright, V. L., & Hildreth, G. J. (1986). Effects of computer-assisted instruction and teacher-assisted instruction on arithmetic task achievement scores of kindergarten children. *Journal of Educational Research*, *80*, 121–125.

McDermott, P. A., & Watkins, M. W. (1983). Computerized versus conventional remedial instruction for learning disabled students. *Journal of Special Education*, *17*, 81–88.

McGaw, B., & Glass, G. V. (1980). Choice of the metric for effect size in meta-analysis. *American Educational Research Journal*, *17*(3), 325–337.

McLean, J. F., & Hitch, G. J. (1999). Working memory impairments in children with specific arithmetic learning difficulties. *Journal of Experimental Child Psychology*, *74*(3), 240–260.

Melhuish, E. C., Sylva, K., Sammons, P., Siraj-Blatchford, I., Taggart, B., Phan, M. B., et al. (2008). The early years. preschool influences on mathematics achievement. *Science (New York, NY)*, *321*(5893), 1161–1162.

Molko, N., Cachia, A., Riviere, D., Mangin, J. F., Bruandet, M., Le Bihan, D., et al. (2003). Functional and structural alterations of the intraparietal sulcus in a developmental dyscalculia of genetic origin. *Neuron*, *40*(4), 847–858.

Morrill, C. S. (1961). Teaching machines: a review. *Psychological Bulletin*, *58*, 363–375.

Mönkkönen, A., Richardson, U., Räsänen, P., Herrera Montes, A., Kujala, J., Brem, S., et al. (in preparation). *Graphogame-Math: Using a computer game for training number skills in preschool aged children*.

Moxley, R., Warash, B., Coffman, G., Brinton, K., & Concannon, K. (1997). Writing development using computers in a class of three-year-olds. *Journal of Computing in Childhood Education*, *8*(2–3), 133–164.

Mazzocco, M. M. M., & Thompson, R. E. (2005). Kindergarten predictors of math learning disability. *Learning Disabilities Research and Practice*, *20*, 142–155.

Nieder, A., & Miller, E. K. (2004). Analog numerical representations in rhesus monkeys: Evidence for parallel processing. *Journal of Cognitive Neuroscience*, *16*(5), 889–901.

Niemiec, R. P., & Walberg, H. J. (1987). Comparative effects of computer-assisted instruction: A synthesis of reviews. *Journal of Educational Computing Research*, *3*, 19–37.

Niemiec, R. P., & Walberg, H. J. (1984). Computers and achievement in the elementary schools. *Journal of Educational Computing Research*, *1*, 435–440.

Okolo, C. (1992). The effects of computer-based attribution retraining on the attributions, persistence, and mathematics computation of students with special needs. *Journal of Special Needs*, *25*(5), 327–334.

Ortega-Tudela, J. M., & Gómez-Ariza, C. J. (2006). Computer-assisted teaching and mathematical learning in down syndrome children. *Journal of Computer Assisted Learning*, *22*, 298–307.

Ostad, S. A. (1998). Developmental differences in solving simple arithmetic word problems and simple number-fact problems: A comparison of mathematically normal and mathematically disabled children. *Mathematical Cognition*, *4*(1), 1–20.

Pape, S. J., & Wang, C. (2003). Middle school children's strategic behavior: Classification and relation to academic achievement an mathematical problem solving. *Instructional Science*, *31*, 419–449.

Passolunghi, M. C., Vercelloni, B., & Schadee, H. (2007). The precursors of mathematics learning: Working memory, phonological ability and numerical competence. *Cognitive Development*, *22*, 165–184.

Pezdek, K., & Stevens, E. (1984). Children's memory for auditory and visual information on television. *Developmental Psychology*, *20*, 212–218.

Piazza, M., Facoetti, A., Trussardi, A.N., et al. (submitted for publication). *Developmental trajectories of number sense in normal and dyscalculic children*.

Piazza, M., Mechelli, A., Butterworth, B., & Price, C. (2002). Are subitizing and counting implemented as separate or functionally overlapping processes? *NeuroImage*, *15*(2), 435–446.

Price, G., Holloway, I., Räsänen, P., Vesterinen, M., & Ansari, D. (2008). Impaired parietal magnitude processing in Developmental Dyscalculia. *Current Biology*, *17*(24), 1042–1043.

Ragosta, M., Holland, P., & Jamison, D. T. (1981). *Computer-assisted instruction and compensatory education*. Princeton: Educational Testing Service.

Randel, J., Morris, B., Wetzel, C. D., & Whitehall, B. (1992). The effectiveness of games for educational purposes: A review of recent research. *Simulation & Gaming*, *23*(3), 261–276.

Reitsma, P., & Wesseling, R. (1998). Eects of computer-assisted training of blending skills in kindergartners. *Scientific Studies of Reading*, *2*(4), 301–320.

Rotzer, S., Kucian, K., Martin, E., von Aster, M., Klaver, P., & Loenneker, T. (2008). Optimized voxel-based morphometry in children with developmental dyscalculia. *NeuroImage*, *39*(1), 417–422.

Rousselle, L., & Noel, M. P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs non-symbolic number magnitude processing. *Cognition*, *102*(3), 361–395.

Shin, N., Norris, C., & Soloway, E. (2006). Effects of handheld games on students learning in mathematics. *Proceedings of the 7th International Conference on Learning Sciences.* Indiana University, Bloomington IN, June 27–July 1.

Shute, R., & Miksad, J. (1997). Computer-assisted instruction and cognitive development in preschoolers. *Child Study Journal*, *27*(3), 237–253.

Suppes, P., Jerman, M., & Brian, D. (1968). *Computer-assisted instruction: the 1965–66 Stanford Arithmetic Program*. New York: Academic Press.

Suppes, P., & Morningstar, M. (1969). Computer-assisted instruction: Two computer-assisted instruction programs are evaluated. *Science*, *166*, 343–350.

Svenson, O., & Sjöberg, K. (1978). Subitizing and counting processes in young children. *Scandinavian Journal of Psychology*, *19*(1), 247–250.

Swanson, H. L., & Jerman, O. (2006). Math disabililities: A selective meta-analysis of the literature. *Review of Educational Research*, *76*(2), 249–274.

VanDerHeyden, A. M., Broussard, C., & Cooley, A. (2006). Further development of measures of early math performance for preschoolers. *Journal of School Psychology*, *44*, 533–553.

Van der Sluis, S., Van der Leij, A., & De Jong, P. F. (2005). Working memory in Dutch children with reading- and arithmetic-related LD. *Journal of Learning Disabilities*, *38*, 207–221.

Vandierendonck, A., Kemps, E., Fastame, M. C., & Szmalec, A. (2004). Working memory components of the corsi blocks task. *British Journal of Psychology*, *95*, 57–79.

van Garderen, D., & Montague, M. (2003). Visual–spatial representation, mathematical problem solving and students of varying abilities. *Special Needs Research & Practice*, *18*(4), 246–254.

Vasilyeva, I., Puuronen, S., Pechenizkiy, M., & Räsänen, P. (2007). Feedback adaptation in web-based learning systems. *International Journal of Continuous Engineering Education and Life-Long Learning*, *17*(4/5), 337–357.

Verguts, T., & Fias, W. (2004). Representation of number in animals and humans: a neural model. *Journal of Cognitive Neuroscience*, *16*(9), 1493–1504.

Vernadakis, N., Avgerinos, A., Tsitskari, E., & Zachopoulou, E. (2005). The use of computer assisted instruction in preschool education: Making teaching meaningful. *Early Childhood Education Journal*, *33*(2), 99–104.

Verschaffel, L., De Corte, E., & Vierstraete, H. (1999). Upper elementary school pupils' difficulties in modeling and solving nonstandard additive word problems involving ordinal numbers. *Journal for Research in Mathematics Education*, *30*(3), 265–285.

Williams, R. A. (1984). Preschoolers and the computer. *Arithmetic Teacher*, *31*(8), 39–42.

Wilska, T. (2003). Mobile phone use as part of young people's consumption styles. *Journal of Consumer Policy*, *26*, 441–463.

Wilson, A. J., Dehaene, S., Pinel, P., Revkin, S. K., Cohen, L., & Cohen, D. (2006). Principles underlying the design of "the number race", an adaptive computer game for remediation of dyscalculia. *Behavioural and Brain Functioning*, *2*(1), 19.

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. *Behavioural and Brain Functioning*, *2*(1), 20.

Xin, Y. P., & Jitendra, A. K. (1999). The effects of instruction in solving mathematical word problems for students with learning problems: A meta-analysis. *Journal of Special Education*, *32*(4), 207–225.

Xin, Y. P., Jitendra, A. K., & Deatline-Buchman, A. (2005). Effects of mathematical word problem-solving instruction on middle school students with learning problems. *Journal of Special Education*, *39*(3), 181–192.

Please cite this article in press as: Räsänen, P., et al. Computer-assisted intervention for children with low numeracy skills. *Cognitive Development* (2009), doi:10.1016/j.cogdev.2009.09.003