MIND, BRAIN, AND EDUCATION

Effects of an Adaptive Game Intervention on Accessing Number Sense in Low-Socioeconomic-Status Kindergarten Children

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ABSTRACT— "The Number Race" is an adaptive game designed to improve number sense. We tested its effectiveness using a cross-over design in 53 low socioeconomic status kindergarteners in France. Children showed improvements in tasks traditionally used to assess number sense (numerical comparison of digits and words). However, there was no improvement on non-symbolic measures of number sense, suggesting that rather than being in number sense per se, the improvement was in number sense access; or links between symbolic and non-symbolic representations of number. Focused adaptive interventions such as this may contribute to reducing the socioeconomic gap in math achievement.

Computer-aided instruction can be a useful tool in early mathematics education, even in preschool and kindergarten (Clements, 2002). Adaptive computer games designed to behaviorally train a particular aspect of cognition hold particular promise, especially for children disadvantaged by learning difficulties or socioeconomic status (SES). Not only do they have the potential to render repetitive training entertaining but they can also individualize instruction by constantly assessing children's performance and adapting task difficulty, thus maintaining each child in his or her "zone of proximal learning." In the reading field, this approach has successfully been used to train children with specific language impairment and dyslexia on phonological processing, resulting in improved reading (Hintikka, Aro, & Lyytinen, 2005; Tallal et al., 1996). This improvement has a neural basis; an increase in brain activity in areas that are underactivated in dyslexia (Temple et al., 2003).

We have developed an analogous behavioral training program for number and elementary arithmetic (Wilson, Dehaene, et al., 2006; Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006). This software, known as "The Number Race," was designed to train children on a core aspect of mathematical cognition; *number sense*. Like adaptive games in reading, the software was designed as a remediation tool for learning disabilities, but may also be useful in other populations associated with low number sense, such as low SES children. In this short report, we describe the first test of this software in a low-SES kindergarten population.

Number Sense

Although researchers and educationalists use the term in a variety of ways (Berch, 2005), most would agree on the broad definition of number sense as the ability to quickly understand, approximate, and manipulate numerical quantities (Dehaene, 1997, 2001). Research in numerical cognition (a branch of cognitive neuroscience) suggests that number sense is one of the important foundations of mathematical cognition

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(Dehaene, 1997; Dehaene, Molko, Cohen, & Wilson, 2004; Gilmore, McCarthy, & Spelke, 2007). The more precise definition of number sense developed in this field is based on brain imaging, comparative, and psychophysical data. Number sense is proposed to be based on a *non-symbolic* quantity representation which is present in animals and very early on in human development (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Feigenson, Dehaene, & Spelke, 2004). In both adults and children, number sense appears to be associated with a specific brain area, the horizontal segment of the intraparietal sulcus (Cantlon, Brannon, Carter, & Pelphrey, 2006; Dehaene, Piazza, Pinel, & Cohen, 2003) In its most elementary form, it can be measured using tasks which involve viewing, comparing, adding, or subtracting non-symbolic numerosities, such as arrays of dots (McCrink, Dehaene, & Dehaene-Lambertz, 2007; Piazza, Pinel, Le Bihan, & Dehaene, 2007). An important measure of the precision of number sense is the *distance effect*, which is the increase in accuracy seen when comparing numerosities which are further apart versus closer together. Evidence suggests that the slope of the non-symbolic distance effect becomes steeper over the course of development (Lipton & Spelke, 2003). The distance effect is still present in adult reaction time to simple symbolic numerical comparison tasks such as deciding which is greater, 3 or 7? (Moyer & Landauer, 1967), suggesting that such tasks draw on number sense (Dehaene, 1992).

We note that at least in the stricter cognitive neuroscience definition of number sense, this approximate representation of magnitude should be distinguished from a different core system that represents small numbers of objects (up to four) within the "object file" system (Feigenson et al., 2004). This system is thought to underlie the human infant and adult ability to subitize, or rapidly perceive the numerosity of small numbers without counting. Thus, for numbers from 1 to 4, there are two systems of representation available, approximate magnitude or number sense, and exact representation of individual objects. (For a detailed review and discussion of the distinction between these two systems, see Feigenson et al., 2004.) During development, the integration of these systems through verbal counting is thought to pave the way to a detailed understanding of exact number (Carey, 2001; Le Corre & Carey, 2007; Lipton & Spelke, 2005).

The importance of number sense is highlighted by the fact that dyscalculia (or mathematical learning disability) is associated with abnormalities in the intraparietal sulcus (Isaacs, Edmonds, Lucas, & Gadian, 2001; Kucian et al., 2006; Molko et al., 2003), and that low number sense in kindergarten (measured with symbolic tasks) is also a predictor of dyscalculia (Mazzocco & Thompson, 2005). Consequently, it has been proposed that the "core deficit" in dyscalculia may be impairment in number sense (Butterworth, 1999; Gersten & Chard, 1999; Molko et al., 2003; Robinson, Menchetti, & Torgesen, 2002; Wilson & Dehaene, 2007).

The educational community has also recognized the importance of number sense, although the term here is used in a much broader sense (Berch, 2005; Gersten, Jordan, & Flojo, 2005). Notably, in reference to the preceding discussion, number sense has often been assessed using only symbolic tests (i.e., using Arabic digits or words), and very rarely with tests which are purely non-symbolic (both stimuli and responses). Notwithstanding, several recent studies suggest that children's early number sense (at least as defined in this broader way) is an important predictor of later math performance (Chard et al., 2005; Jordan, Kaplan, Olah, & Locuniak, 2006).

Number Sense and SES

Low number sense is more common in kindergarten children from low-SES families (Griffin, Case, & Siegler, 1994; Jordan et al., 2006), as are other lower scores on a variety of mathematical tasks (Denton & West, 2002; Jordan, Huttenlocher, & Levine, 1994). This association between low SES and low mathematics performance continues into elementary and high school (Starkey, Klein, & Wakeley, 2004), and may play a role in limiting children's career prospects.

Given the risks associated with low number sense, it is important to find out what are the best methods to increase it, particularly in the preschool or kindergarten years. This is especially important because while most children show improvements in number sense-related tasks in the course of development (Huntley-Fenner, 2001; Lipton & Spelke, 2003; Sekuler & Mierkiewicz, 1977; Siegler & Booth, 2004; Siegler & Opfer, 2003), children with low number sense appear to show very little spontaneous improvement (Jordan et al., 2006).

Access to Number Sense

A key development which must occur during human learning is the association between non-symbolic number sense and the cultural symbols which represent number (e.g., number words and Arabic digits). Much evidence suggests that in normal adults, this activation has become strongly automatic (e.g., Dehaene & Akhavein, 1995; Naccache & Dehaene, 2001; Pavese & Umiltà, 1998; Rusconi, Priftis, Rusconi, & Umiltà, 2006). Young children also appear to access non-symbolic representations of numbers when solving problems presented in Arabic or verbal form, even in kindergarten (Gilmore et al., 2007), but the automaticity of the conversion from symbols to quantities is not yet established in early childhood (Girelli, Lucangeli, & Butterworth, 2000; Moyer & Landauer, 1967; Rousselle & Noël, 2007) and is reduced in dyscalculic adults (Rubinsten & Henik, 2005, 2006). Consistent with previous authors (Rousselle & Noël, 2007), we refer to this conversion as *number sense access*.

The distinction between number sense per se versus number sense access (analogous to the neuropsychological distinction between a pure semantic impairment versus a disconnection syndrome) has only recently begun to be highlighted in the developmental literature (Rousselle & Noël, 2007; Wilson & Dehaene, 2007). However, it is of both theoretical and applied importance. In both the numerical cognition and education fields, the cognitive tasks which have been traditionally used to measure "number sense" are confounded with number sense access, because they involve symbolic representation of number (e.g., comparison of Arabic digits/number words, verbal labeling of numbers, or counting). It is for this reason that much work in numerical cognition is now focusing on non-symbolic measures (Barth et al., 2006; Cantlon et al., 2006; McCrink & Wynn, 2004; Piazza et al., 2007) and that the use of non-symbolic tests has been advocated as a more direct measure of number sense in children (Wilson & Dehaene, 2007). Ideally, tests designed to purely measure number sense should involve large numerosities (e.g., groups of dots), with brief presentation times in order to eliminate other enumeration processes such as counting (while employing controls for visual variables such as density, size of objects, etc.). To measure number sense access, one can compare results from such tests to those from tests involving symbolic stimuli.

Number sense access has been suggested to be an alternative core deficit in dyscalculia (Rousselle & Noël, 2007; Rubinsten & Henik, 2005). It may also be more plausible as the cause of the low "number sense" observed in low-SES children, who may have less experience with symbolic numbers than their high-SES counterparts. This hypothesis is supported by early work by Jordan and colleagues (Jordan, Huttenlocher, & Levine, 1992; Jordan et al., 1994), who showed that although low-SES kindergarteners scored lower than high-SES kindergarteners on small addition and subtraction problems presented in verbal format (both stimulus and response), performance of the two groups did not differ for problems presented in a non-verbal format.

Interventions in Low-SES Populations

Several previous studies have shown that curriculum-level interventions can improve early "number sense" in low-SES kindergarten children. The "RightStart" curriculum was designed by Griffin et al. (1994; now known as "NumberWorlds," Griffin, 2004) to compensate for a lack of environmental experience placing an emphasis on early mathematical skills. The intervention consisted mostly of classroom games (e.g., board games) which emphasized the relationship between counting and quantity, and between number and space, in a variety of situations. Games also emphasized children's active participation and encouraged social interactions about quantity. Low-SES children who were taught with this curriculum in kindergarten (30 weeks of daily instruction) overtook their peers on number sense scores (measured mostly by symbolic numerical comparison) and remained ahead 3 years later (Griffin et al., 1994).

Sarama and Clements (2002, 2004) developed another research-based pre-kindergarten curriculum, "Building Blocks," composed primarily of computer activities (as well as manipulatives and print), and focusing on number and geometry. A recent study tested its effects in low-SES preschoolers (3- to 4-year old), over the course of 1 year (Clements & Sarama, 2007). The number assessment test used in this study included several non-symbolic measures. Low-SES children taught with the "Building Blocks" curriculum showed much larger gains in a set of number tasks compared with those taught with a control curriculum. Analysis of individual tasks suggested that there was an effect of the curriculum on tasks requiring number sense or number sense access, such as subitizing, non-symbolic numerosity ordering (arranging cards with groups of 1–5 dots in numerical order), and matching number digits with groups of dots. Despite the fact that non-symbolic stimuli were used in these tests, their results cannot be used to distinguish between an improvement in number sense versus number sense access, because children may have been able to count in the non-symbolic tasks.

It is clear that research-based curriculum-level interventions such as these benefit the mathematical development of low-SES children. However, they involve a considerable investment of resources, and are adapted to the class and not to the individual. They also include a large number of instructional factors. Although each factor is likely to make some contribution to mathematical and/or overall cognitive development, not all factors may be necessary or sufficient for an improvement in number sense or number sense access.

An exception to this approach is work conducted concurrently to our own by Siegler and Ramani, who aimed to isolate a key instructional factor in Griffin et al., (1994) successful earlier intervention. Four-year-old low SES children were given four 15 min sessions of intervention playing a simple game which either involved counting along a board with squares numbered 1–10, or matching colors on a board with colored squares (Siegler & Ramani, 2008). Children who received the number intervention showed a large increase in accuracy placing numbers on number lines (Siegler & Booth, 2004; Siegler & Opfer, 2003) compared with those who received the color intervention (Siegler & Ramani, 2008). A second study replicated this finding, and also showed lasting improvement on number identification, counting, and numerical comparison (Ramani & Siegler, 2008). Low-SES children were shown to exhibit less accurate performance on the number line task than high-SES children (Siegler & Ramani, 2008). Task performance was also shown to be positively correlated with other number sense tasks and math achievement (Booth & Siegler, 2006; Laski & Siegler, 2007), and predictive of acquisition of new material (Booth & Siegler, 2008).

An independent study based on this work (Whyte & Bull, 2008) also recently showed that the mapping of number to space provided by the board game format was likely to be the particular instructional factor responsible for an improvement on number line placement. However, mapping of non-symbolic number to Arabic digits in a different card game still resulted in equivalent improvements in counting and Arabic digit naming, as well as in symbolic numerical comparison (with Arabic digits).

These results clearly show that board games with counting and numbered squares produce an improvement in either number sense or number sense access. However, it is not clear which, because none of the outcome tasks are purely non-symbolic. For instance, changes in performance on the number line task may reflect changes in the underlying representation of number or the mapping of symbolic number to this representation (e.g., Izard & Dehaene, 2008).

"The Number Race"

We designed our software "The Number Race" as a targeted intervention with a minimal combination of instructional factors focused on core aspects of number sense, outlined below (Wilson, Dehaene et al., 2006) (Figure 1). The software allows for individualization of instruction by using a multidimensional algorithm to continually model the current state of the child's knowledge and adapt difficulty correspondingly. Children can use it with minimal supervision, making it suitable for home or classroom use. It is freely available for teachers and parents anywhere to download and use, and for others to develop, and can be downloaded directly from http://www.unicog.org/main/pages.php?page=NumberRace. It has thus far been translated into seven different languages: English, Dutch, Finnish, French (original version), German, Greek, and Spanish.

The instructional principles behind "The Number Race" were based on research in numerical cognition as well as some aspects of the work of Griffin et al. (1994). They include: (1) an emphasis on number sense, including numerical comparison (deciding which is the bigger of two numbers) and the link between number and space; (2) cementing links between non-symbolic and symbolic representations of number; and (3) increasing understanding of and fluency of access to basic addition and subtraction facts.

Difficulty is constantly adapted using a multidimensional adaptive algorithm, so that the success rate of each child stays at around 75%. There are three different difficulty dimensions: numerical distance between the two numbers presented, speed of the response deadline, and ratio of symbolic to non-symbolic numbers.

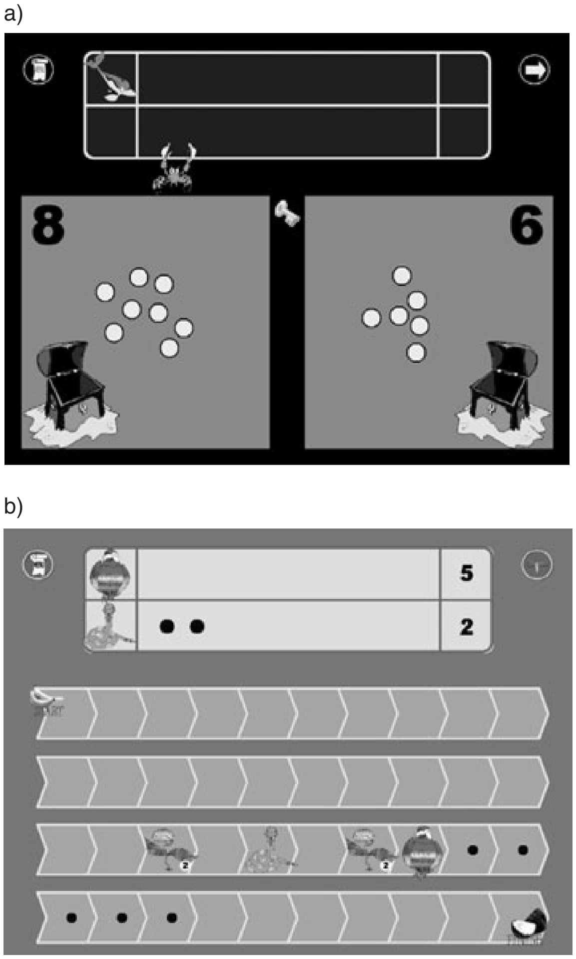

Fig. 1. Screenshots from "The Number Race". Children choose to play in one of two entertaining game worlds. In both, they have to advance in a race against the computer by choosing the larger of two numbers from 1 to 9 which are presented to them (a). These are initially presented non-symbolically as groups of dots, but as children progress they are forced to rely on symbolic representations (words and digits) to make their choice, eventually relying solely on digits. Once they make a response, they are presented with all three number formats (dots, words, and written numbers). As the game becomes more difficult, they have to respond faster and faster, before their competitor (controlled by the computer) steals the larger number. Once children have made a choice, they use tokens gained during the comparison phase to move forward on a playing board by an equivalent number of cells (thus, training number–space mappings and one-to-one correspondence) (b). If children reach the finish line before the enemy character does, they can collect a reward item, which contributes toward unlocking a new character to play with. In higher levels, addition and subtraction problems are introduced.

The Current Study

In our previous work, we tested the efficacy of the software in 7- to 9-year-old children with mathematical difficulties with promising initial results (Wilson, Revkin et al., 2006).

Pre- to post-test improvement was seen on several number sense and number sense access tasks: number comparison (symbolic and non-symbolic), enumeration of small quantities (subitizing), and subtraction of one-digit numbers. In the current study, we tested whether "The Number Race" could also boost number sense and/or number sense access in younger children (kindergartners) from low-SES families. If this is the case, it provides us with information about the minimal factors required to produce an increase in number sense in this population, as well as providing educators and parents with non-curricular options for targeted, individual intervention. By comparing results from symbolic versus non-symbolic tests, we will be able to infer whether it is number sense or number sense access which has improved in this population.

METHOD

We used a two-period cross-over design, with a commercial reading software package as a control. Children were tested before the study (T1). For the first half of the study, one group was instructed with the math software and another with the reading software. Children were then tested mid-study (T2), and the instruction software for each group was swapped for the second half of the study. Children were then given a final test (T3).

Sample

Participants were 53 (4- to 6-year-old) children (24 girls and 29 boys) attending the final year of two kindergartens in Clermont-Ferrand, France. The mean age was 5.6 years ($SD = 0.4$ years). Parents gave informed written consent for their child's participation.

The kindergartens were both situated in an "education priority zone," a categorization made by the education department of the French government for areas which face particularly difficult social and economic conditions and associated high rates of school failure (Bénabou, Kramarz, & Prost, 2004). Children in these zones often come from immigrant families and have a first language other than French (based on experimenter observation, this was the case for 43% of children in the present study).

Control Software

The control software was a commercially available kindergarten reading package, "Lapin Malin: Voyage au pays de la lecture" (Mindscape, 2000). It included exercises in listening to phonemes, word assembly, auditory segmentation, phoneme/grapheme matching, and word reading.

Procedure

The study took place at school during kindergarten hours over a period of 14 weeks. Children were divided into two groups based on their school (random assignment to group was not possible due to practical constraints). One group used the math software in the first phase then the reading software in the second phase, and vice versa for the second group. Instruction sessions were in groups of three children (math) or two children (reading), supervised by one of the authors (O.D.). Each child had a total of six sessions with the math software, and four sessions with the control software. Sessions were 20 min. Children worked independently on a laptop with headphones, whereas the supervisor provided encouragement and ensured that they maintained attention and motivation. Care was taken to ensure that this interaction consisted only of general encouragement, reorientation of attention, and comments regarding progress with the software (e.g., "wow, you've nearly finished the game!").

Pre-, Mid-, and Post-Testing

At each testing point, a brief half-hour paper and pencil testing battery was administered in French, either by one of the authors (O.D.) or by one of two psychology masters students. The measures in this battery focused on number sense (and number sense access), and included some brief assessments of other tasks. *Written and verbal symbolic numerical comparison* tasks assessed both number sense and its access. Each had 20 items, and involved choosing the larger of 2 one-digit numbers (1–9), presented as digits or verbally. Number sense was also measured directly using a *non-symbolic comparison* task (18 items), which involved rapidly choosing the larger of two random dot patterns (8–32 dots; children instructed not to count). To reduce non-numerical cues, the two dot patterns presented on a given trial were matched either on total occupied area and luminosity, or on dot density and size. All comparison tests included a variety of internumerical distances.

Links between symbolic number representations were assessed using a *cross-format matching* test, in which children had to say whether two numbers (1–9) presented in different formats (dots, digits, or words) were the same. Each of the three possible pairs of stimuli types (dot-digit, dot-verbal, and word-digit) had six items. For pairs including dots, children were first asked how many dots there were and allowed to count them, and then if the digit or word meant the same thing.

Verbal counting was assessed by asking children to count as far as possible, to count up to 7, to count from 4, and to count from 3 to 8. *Object counting* was assessed by asking children to count six randomly arranged objects. They were scored for a correct verbal sequence and correct pointing. Understanding of counting principles was assessed by asking ("How many trees are there altogether?," and "How many if you had started over there?"). *Addition* was measured by five simple verbal problems (e.g., "how much is three plus five?").

Tasks were presented in the following order: Verbal counting, object counting, non-symbolic numerical comparison, digit numerical comparison, verbal numerical comparison, cross-format number matching, and addition.

RESULTS

Children's percentage error was calculated for each task at each time point (T1, T2, and T3) and was analyzed using mixed 2 × 3 (experimental group × time point) analyses of variance (ANOVAs), including planned linear and quadratic contrasts for the time point variable. In a classic "cross-over" effect, one expects to see an opposite pattern of improvement over time for the two experimental groups: over the period T1–T2, the "math then reading" group should show a greater improvement than the "reading then math" group, whereas conversely, during the period T2–T3, one would expect to see the opposite effect. The direct statistical test for this effect is the interaction between experimental group and the quadratic contrast of time point (hereafter, referred to as "quadratic interaction").

Symbolic Numerical Comparison

Symbolic comparison results are shown in Figure 2. Both the digit symbolic comparison and the verbal numerical comparison tasks showed a clear cross-over effect. In digit numerical comparison (Figure 2a), the quadratic interaction was significant ($F[1, 51] = 5.28, p = .03$), and post hoc *T*-tests showed that this was principally driven by changes across the respective intervention periods for each group, the T1–T2 difference being highly significant for the "math then reading" group ($t[1, 26] = 3.55$, $p = .001$), and the T2–T3 difference marginal for the "reading then math" group ($t[1, 25] = 1.69$, $p = .10$). There was no significant intergroup difference at T1.

The verbal numerical comparison results (Figure 2b) were similar, with a significant quadratic interaction ($F[1, 51] = 7.21$, $p = .01$). Again, post hoc *T* tests showed that the quadratic interaction was principally driven by changes across the respective intervention periods for each group, the T1–T2 difference being highly significant for the "math then reading" group ($t[1, 26] = 3.58$, $p = .001$), and the T2–T3 difference significant for the "reading then math" group ($t[1, 25] = 2.21$, $p = .04$). There was no significant intergroup difference at T1.

For both tasks, we conducted an a priori analysis to test whether there was a change in the size of the numerical distance effect (which would indicate an increase in precision of number sense) by sorting items into two distance categories, "near" and "far." We calculated the size of the distance effect at each time point by subtracting the error rate for the "far" numerosity from that of the "near" numerosity. In the Arabic digit comparison task, there was a significant main effect of time point ($F[2, 102] = 4.37, p = .02$), with the distance effect showing a steady reduction over time. However, there was no interaction with experimental group. The verbal numerical comparison task did not show any changes in the size of the distance effect across time or any interaction with group.

We also conducted a post hoc analysis to examine whether the software had benefited the lowest performing children the most (Figure 2c and d). Each experimental group was split into a "high error" and "low error" subgroup ($n = 13$ or 14 in each), using a median split of the average score across all math tests at T1. We found that the "high error" subgroup of children showed a large cross-over pattern, with considerable improvement during the math intervention, and almost none during the reading intervention. This quadratic interaction bordered significance for the digit comparison task ($F[1, 24] = 4.05$, $p = .056$) and was significant for the verbal comparison task ($F[1, 24] = 4.76$, $p = .04$). In the "low error" subgroup, the "math then reading" children showed a similar, but smaller, effect; however, children in the "reading then math" group were at ceiling at all time points, including T1.

Non-Symbolic Numerical Comparison

The non-symbolic comparison results are shown in Table 1. Results showed a significant linear interaction ($F[1, 50] = 6.86$, $p = .01$), but the quadratic interaction was not significant. The overall changes in performance were small compared with those in the symbolic tasks. There was no change in the size of the distance effect for this task.

These results, coupled with the lack of a change in distance effect in the symbolic tasks, suggest that the software may have resulted in improvements in access to number sense via symbolic information, rather than in number sense per se.

Counting

Consistent with the theory that counting appears to be a process which draws more heavily on verbal than on number sense capacities (Dehaene, 1992; Dehaene et al., 2003), the verbal counting task (Table 1) showed a significant quadratic interaction in the opposite direction to that of the number sense tasks ($F[1, 51] = 4.88$, $p = .03$); i.e., more improvement was seen during training with the control reading software than with "The Number Race" software. Post hoc *T* tests revealed that the interaction was primarily driven by the T2–T3 change for the "math then reading group" ($t[1, 26] = 5.20$, $p < .001$), whereas for the "reading then math group" both the T1–T2 and T2–T3 periods showed significant changes ($t[1, 25] = 3.43, p = .002$; and $t(1, 25) = 4.06$, $p < .001$, respectively). There was no

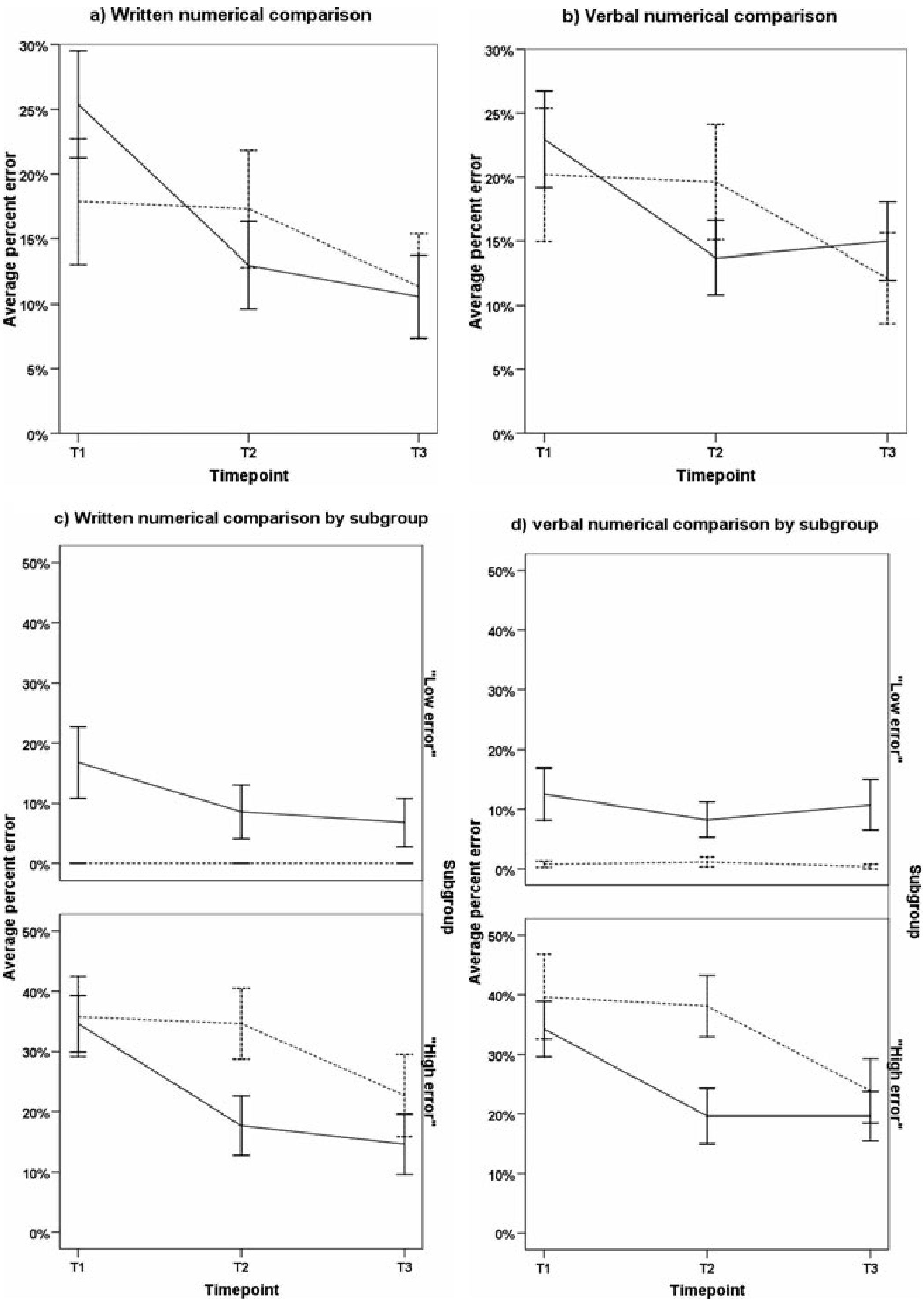

Fig. 2. Symbolic numerical comparison effects; overall for digit comparison (a), and verbal comparison (b); and broken down by subgroup for the same two tasks (c and d). Subgroup was determined by a median split of average T1 error rates. Error bars indicate one standard error.

significant intergroup difference at T1. Unlike the symbolic comparison tasks, this effect was strongest for the "low error" subgroup, which showed a clear significant quadratic interaction ($F[1, 25] = 6.71$, $p = .02$). In contrast, children in the "high error" subgroup showed only a main effect of time point ($F[2, 48] = 39.54$, $p < .001$). Results from object counting (Table 1) showed only a main effect of time point ($F[2, 102] = 3.36, p = .04$).

Table 1
Average Percent Error by Timepoint and Group

	T1 (%)	T2 (%)	T3 (%)
Written (digit) number comparison			
"Math then reading" group	25 (4%)	13 (3%)	11 (3%)
"Reading then math" group	18 (5%)	17 (4%)	11 (4%)
Verbal number comparison			
"Math then reading" group	23 (4%)	14 (3%)	15 (3%)
"Reading then math" group	20 (5%)	20 (4%)	12 (4%)
Non-symbolic comparison (dots) ($n = 52$)[a]			
"Math then reading" group	23 (1%)	20 (1%)	18 (1%)
"Reading then math" group	19 (1%)	22 (1%)	20 (1%)
Verbal counting			
"Math then reading" group	51 (5%)	50 (4%)	24 (5%)
"Reading then math" group	42 (5%)	27 (6%)	12 (4%)
Object counting			
"Math then reading" group	18 (4%)	23 (6%)	12 (3%)
"Reading then math" group	26 (5%)	20 (5%)	14 (4%)
Cross-format matching			
"Math then reading" group	21 (4%)	10 (2%)	11 (3%)
"Reading then math" group	9 (3%)	7 (2%)	5 (1%)
Addition			
"Math then reading" group	93 (4%)	84 (4%)	76 (5%)
"Reading then math" group	68 (7%)	63 (9%)	52 (8%)

Note. Scores are average percent error. Parentheses contain standard error.
[a]One subject was excluded from this analysis due to outlying scores (at chance level).

Cross-Format Matching

The cross-format matching data are shown in Table 1. The data were analyzed non-parametrically because the distributions were skewed and kurtotic (a large number of responses were at ceiling). The quadratic contrast was calculated directly for each subject (score $= \mathrm{T1} - 2\mathrm{T2} + \mathrm{T3}$), and the group difference for this contrast was significant (Mann–Whitney $U = 233.5$, $p = .04$). These results are consistent with improved links between different number representations, although they were driven principally by the "math then reading" group.

Addition

The addition data are shown in Table 1. No significant interaction was found, although the main effect of time point was significant ($F[2, 102] = 12.60, p < .001$), reflecting a steady increase in performance across the period of the study, as was the main effect of group ($F[1, 51] = 7.61, p = .008$), with the "math then reading" group showing consistently lower scores. Initially, this lack of specific improvement seemed surprising because addition is included in higher levels of the math software. However, on average, children were exposed to these higher levels on only 10 occasions (or 8% of game turns) during the entire instructional period, which may not have been enough to result in improvement.

DISCUSSION

Our results strongly suggest that "The Number Race" adaptive game software improved kindergarten children's performance on symbolic numerical comparison tasks, which have traditionally been used to measure number sense. The use of a cross-over design means it is unlikely that improvement was solely due to other factors such as initial differences between groups, normal development, class teaching, test–retest effects, or regression to the mean. The control reading software also allows us to conclude that improvement could not have been solely due to computer use in general or to extra attention from the supervisor. The benefit of the software was substantial, especially in children who started off with lower performance, and considering that the software was only used for a small number of short sessions. Long-term maintenance of the benefit remains to be evaluated, but it showed at least short-term durability because in the "math then reading" group the improvements in the T1–T2 period still held 6 weeks later at T3.

These findings are consistent with the earlier and current work showing that board games have a positive effect on number sense in low-SES children (Griffin et al., 1994; Ramani & Siegler, 2008; Siegler & Ramani, 2008). However, an added advantage of the current study was that it permitted examination of whether improvements were likely due to number sense per se or to number sense access. An improvement in number sense per se would manifest itself in improvement on non-symbolic numerical comparison tasks and a change in the size of the symbolic distance effect, a classic indicator of the precision of number sense. However, there was no effect seen on the non-symbolic numerical task, and although overall accuracy of symbolic numerical comparison increased, there was no specific change in the distance effect.

Overall, these results suggest that the source of the low "number sense" found in low-SES children may in fact be a difficulty in number sense access, or in linking symbolic representations to their representation of quantity. This would make sense, because there is no a priori reason to believe that low-SES children would have poor non-symbolic number sense at entry to kindergarten. However, it is likely that they may have been less exposed to symbolic number in the home.

An alternative interpretation is that, irrespective of the population tested, "The Number Race" software improves only access to number sense and not number sense per se. This possibility should be considered in future work but seems unlikely given previous results with the software in dyscalculic children (Wilson, Revkin et al., 2006), which showed improvement on non-symbolic as well as symbolic tasks.

Consistent with the hypothesis that counting draws more heavily on verbal skills than number sense skills (Dehaene, 1992; Dehaene et al., 2003), we observed a reverse cross-over effect for the verbal counting task, with children improving more on this task during the period of the reading remediation. Although this effect may be due to the reading intervention benefiting verbal representation of number, it should be interpreted with caution, because the results might also reflect verbal comprehension. (For instance to answer "can you count from 3 to 8?" correctly, children need to have a very precise understanding of "from" and "to".)

Limitations and Future Directions

There are three main limitations of the current study. The first is that the reading and mathematics software sessions differed slightly in the total intervention time and number of children present. Notwithstanding, for these general factors to have driven the findings observed, one would have to explain why they would specifically affect some tasks tested and not others. The second is the randomized assignment of schools rather than individual children to the two experimental conditions. This design feature, adopted for practical purposes, opens up the possibility that one school could have focused more on maths during the first half of the study, and the other in the second. Although this possibility cannot be completely ruled out, to the best of our knowledge there were no changes to the instructional syllabus in the kindergartens concerned, and the amount of time spent on reading and math in the classroom remained the same throughout the study. Barring any factors correlated with the cross-over periods, the use of a cross-over design generally guards against inequalities in groups produced by non-random assignment.

The third limitation relates to generalizability of the results to all children of low SES. Representative of the low-SES population throughout France, some of the children in our sample were not being schooled in their first language, a situation which might pose particular problems for linking verbal representations in the second language to number sense. The extent to which the software would also be beneficial for low-SES children learning in their first language must therefore be verified in future studies. However, the fact that effects were just as strong in the Arabic digit comparison task (likely to be independent of language) suggests that they would generalize to the population of all low-SES children. In addition, we performed additional post hoc splits of the data which suggested that cross-over effects were present both for children who had French as a first language, and for children who did not, with a similar improvement in both groups.

Beyond these limitations, our findings should be seen in the context of the converging findings earlier discussed, which were under very strict experimental control (Ramani & Siegler, 2008; Siegler & Ramani, 2008; Whyte & Bull, 2008). The present work can be considered as a natural complement to this analytic research focusing on particular instructional factors; it uses a richer game with a greater instructional content (and therefore more educational scope and practical impact), but suffers from the difficulty of pinpointing precisely which instructional feature is responsible for the effects found.

Finally, future studies should examine the extent of transfer to other mathematical tasks (both in the short- and long-term), and the duration of improvement. Although we saw limited transfer on some measures, these were for the most part those focused on number sense or number sense access. However, most other measures tended to have only a small number of items, and thus might have shown evidence of transfer with more sensitivity. Transfer might also occur over the long-term, for instance, improved number sense may help children benefit from instruction to addition and subtraction in grade 1. Given that number sense measures are predictive of later school success (Chard et al., 2005; Jordan et al., 2006), we hypothesize that this would be the case. These issues need to be addressed in further research, with a larger test battery and an extended longitudinal design.

Another issue is whether one or both of the two core number systems discussed in the introduction (the "object file" and "approximate magnitude" systems) might be enhanced by "The Number Race" software. Dyscalculic populations have been shown to have difficulties linked to both systems and, in previous work (Wilson, Revkin et al., 2006), we found that after using the software, children with mathematical difficulties showed evidence of improvement in both of these systems, with an increase in subitizing speed and in the speed and precision of non-symbolic comparison of large numbers. Likewise, it is possible that low-SES children might have less well-established links to one or other system, or to both systems. Unfortunately, the measures used in the current study did not permit a clear separation of the two systems. Over the course of development, the two core non-symbolic systems of number interact with the acquisition of verbal counting to produce an "educated" understanding of number (Le Corre & Carey, 2007). How exactly this process goes wrong in dyscalculia and in low-SES populations is an important question for future research.

CONCLUSION

The present study was the first controlled study of "The Number Race" software in kindergarteners, and our main goal was to evaluate whether it could help low-SES kindergarteners at risk for mathematics difficulties. Overall, results from the study suggest that "The Number Race" software can be used for targeted instruction of number sense and number sense access in low-SES kindergarten children. The children who benefited most from the instruction were those who had the highest error rates at the beginning of the study. The results suggest that this improvement is in number sense access, rather than in number sense per se. The positive effect observed means that it will be valuable to engage in further research on this topic, which ideally would aim to replicate the current findings using a stricter randomized experimental design, including only children learning in their first language, and also follow-up measurements.

Although a targeted cognitive intervention such as our software is not intended to replace large-scale curricular interventions, it carries several benefits. On the research side, it allows us to make inferences about which minimal factors are important in contributing to number sense development. On the practical side, it can offer individualized instruction on core cognitive components for children who are lagging behind. As such it may be a useful curricular supplement for teachers and parents.

Acknowledgments Funding for development and testing of The Number Race was provided by INSERM, the Louis D Prize of the Institut de France, and a McDonnell Foundation centennial fellowship to S.D., as well as a Fyssen Foundation postdoctoral award to A.W. In addition, we gratefully acknowledge a consultancy contract to A.W. from the Brain and Learning Project of the OECD. Valuable software development input was provided by many colleagues including Bruce McCandliss, Michael Posner, Sharon Griffin, Dan Schwartz, Joan Davis, Pekka Räsänen, Alex Masloff, Andry Vertiy, Caroline Jacubek, Philippe Pinel, Laurent Cohen, and David Cohen. We gratefully acknowledge the people who contributed to the present project: Pauline Courbeyrie, Jessica Dos Santos, Romain Taillardat, Lucie Machuron, Coraline Cabello, Josie Bernicot, and Guy Chazoule. We are also grateful to participating staff (Geneviève Bégon, Catherine Roux, Christine Nauton) and pupils of the Jean De La Fontaine and Chanteranne schools.

REFERENCES

Barth, H., La Mont, K., Lipton, J., Dehaene, S., Kanwisher, N., & Spelke, E. (2006). Non-symbolic arithmetic in adults and young children. *Cognition*, *98*, 199–222.

Bénabou, R., Kramarz, F., & Prost, C. (2004). Zones d'éducation prioritaire: Quels moyens pour quels résultats? *Économie et Statisque*, *380*, 3–34.

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

Booth, J. L., & Siegler, R. S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology*, *42*(1), 189.

Booth, J. L., & Siegler, R. S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development*, *79*, 1016.

Butterworth, B. (1999). *The mathematical brain*. London: Macmillan.

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. (2001). Cognitive foundations of arithmetic: Evolution and ontogenesis. *Mind and Language*, *16*(1), 37–55.

Chard, D. J., 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*(2), 3–14.

Clements, D. H. (2002). Computers in early childhood mathematics. *Contemporary Issues in Early Childhood*, *3*, 160–181.

Clements, D. H., & Sarama, J. (2007). Effects of a preschool mathematics curriculum: Summative research on the "Building Blocks" project. *Journal for Research in Mathematics Education*, *38*, 136–163.

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, *44*(1–2), 1–42.

Dehaene, S. (1997). *The number sense: How the mind creates mathematics*. Oxford, UK: Oxford University Press.

Dehaene, S. (2001). Précis of the number sense. *Mind and Language*, *16*, 16–36.

Dehaene, S., & Akhavein, R. (1995). Attention, automaticity, and levels of representation in number processing. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *21*, 314–326.

Dehaene, S., Dehaene-Lambertz, G., & Cohen, L. (1998). Abstract representations of numbers in the animal and human brain. *Trends in Neurosciences*, *21*, 355–361.

Dehaene, S., Molko, N., Cohen, L., & Wilson, A. J. (2004). Arithmetic and the brain. *Current Opinion in Neurobiology*, *14*, 218–224.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology*, *20*, 487–506.

Denton, K., & West, J. (2002). *Children's reading and mathematics achievement in kindergarten and first grade*. Washington, DC: National Center for Education Statistics.

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, *8*, 307–314.

Gersten, R., & Chard, D. (1999). Number sense: Rethinking arithmetic instruction for students with mathematical disabilities. *The Journal of Special Education*, *33*(1), 18.

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

Gilmore, C. K., McCarthy, S. E., & Spelke, E. S. (2007). Symbolic arithmetic knowledge without instruction. *Nature*, *447*(7144), 589–591.

Girelli, L., Lucangeli, D., & Butterworth, B. (2000). The development of automaticy of accessing number magnitude. *Journal of Experimental Child Psychology*, *76*, 104–122.

Griffin, S. A. (2004). Building number sense with Number Worlds: A mathematics program for young children. *Early Childhood Research Quarterly*, *19*(1), 173.

Griffin, S. A., Case, R., & Siegler, R. S. (1994). Rightstart: Providing the central conceptual prerequisites for first formal learning of arithmetic to students at risk for school failure. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 25–49). Cambridge, MA: MIT Press.

Hintikka, S., Aro, M., & Lyytinen, H. (2005). Computerized training of the correspondences between phonological and orthographic units. *Written Language and Literacy*, *8*, 155.

Huntley-Fenner, G. (2001). Children's understanding of number is similar to adults' and rats': numerical estimation by 5–7-year-olds. *Cognition*, *78*(3), B27–B40.

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

Izard, V., & Dehaene, S. (2008). Calibrating the mental number line. *Cognition*, *106*, 1221–1247.

Jordan, N. C., Huttenlocher, J., & Levine, S. C. (1992). Differential calculation abilities in young children from middle- and low-income families. *Developmental Psychology*, *28*, 644–653.

Jordan, N. C., Huttenlocher, J., & Levine, S. C. (1994). Assessing early arithmetic abilities: Effects of verbal and nonverbal response types on the calculation performance of middle- and low-income children. *Learning & Individual Differences*, *6*, 413–432.

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

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.

Laski, E. V., & Siegler, R. S. (2007). Is 27 a big umber? Correlational and causal connections among numerical categorization, number line estimation, and numerical magnitude comparison. *Child Development*, *78*, 1723 (1721).

Le Corre, M., & Carey, S. (2007). One, two, three, four, nothing more: An investigation of the conceptual sources of the verbal counting principles. *Cognition*, *105*, 395–438.

Lipton, J. S., & Spelke, E. (2003). Origins of number sense: Large-number discrimination in human infants. *Psychological Science*, *14*, 396–401.

Lipton, J. S., & Spelke, E. S. (2005). Preschool children's mapping of Number Words to nonsymbolic numerosities. *Child Development*, *76*, 978.

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

McCrink, K., & Wynn, K. (2004). Large-number addition and subtraction by 9-month-old infants. *Psychological Science*, *15*, 776–781.

McCrink, K., Dehaene, S., & Dehaene-Lambertz, G. (2007). Moving along the number line: Operational momentum in nonsymbolic arithmetic. *Perception & Psychophysics 69*, 1324–1333.

Mindscape. (2000). *Lapin Malin: Voyage au pays de la lecture*. Boulogne Billancourt, France: Mindscape.

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*, 847–858.

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature*, *215*(5109), 1519–1520.

Naccache, L., & Dehaene, S. (2001). The priming method: Imaging unconscious repetition priming reveals an abstract representation of number in the parietal lobes. *Cerebral Cortex*, *11*, 966–974.

Pavese, A., & Umiltà, C. (1998). Symbolic distance between numerosity and identity modulates Stroop interference. *Journal of Experimental Psychology: Human Perception & Performance*, *24*, 1535–1545.

Piazza, M., Pinel, P., Le Bihan, D., & Dehaene, S. (2007). A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron*, *53*, 293.

Ramani, G. B., & Siegler, R. S. (2008). Promoting broad and stable improvements in low-income children's numerical knowledge through playing number board games (Report). *Child Development*, *79*, 375 (320).

Robinson, C. S., Menchetti, B. M., & Torgesen, J. K. (2002). Toward a two-factor theory of one type of mathematics disabilities. *Learning Disabilities: Research and Practice*, *17*, 81.

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

Rubinsten, O., & Henik, A. (2005). Automatic activation of internal magnitudes: A study of developmental dyscalculia. *Neuropsychology*, *19*, 641.

Rubinsten, O., & Henik, A. (2006). Double dissociation of functions in developmental dyslexia and dyscalculia. *Journal of Educational Psychology*, *98*, 854.

Rusconi, E., Priftis, K., Rusconi, M. L., & Umiltà, C. (2006). Arithmetic priming from neglected numbers. *Cognitive Neuropsychology*, *23*, 227.

Sarama, J., & Clements, D. H. (2002). Building blocks for young children's mathematical development. *Journal of Educational Computing Research*, *27*, 93–110.

Sarama, J., & Clements, D. H. (2004). Building blocks for early childhood mathematics. *Early Childhood Research Quarterly*, *19*(1), 181.

Sekuler, R., & Mierkiewicz, D. (1977). Children's judgments of numerical inequality. *Child Development*, *48*, 630–633.

Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development*, *75*, 428–444.

Siegler, R. S., & Opfer, J. E. (2003). The development of numerical estimation: evidence for multiple representations of numerical quantity. *Psychological Science*, *14*, 237–243.

Siegler, R. S., & Ramani, G. B. (2008). Playing linear numerical board games promotes low-income children's numerical development. *Developmental Science*, *11*, 655–661.

Starkey, P., Klein, A., & Wakeley, A. (2004). Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention. *Early Childhood Research Quarterly*, *19*(1), 99.

Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, X., Nagarajan, S. S., et al. (1996). Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science*, *271*(5245), 81–84.

Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., Merzenich, M. M., et al. (2003). Neural deficits in children with dyslexia ameliorated by behavioral remediation: evidence from functional MRI. *Proc Natl Acad Sci U S A*, *100*, 2860–2865.

Whyte, J. C., & Bull, R. (2008). Number games, magnitude representation, and basic number skills in preschoolers. *Developmental Psychology*, *44*, 588–596.

Wilson, A. J., & Dehaene, S. (2007). Number sense and developmental dyscalculia. In D. Coch, G. Dawson, & K. Fischer (Eds.), *Human behavior, learning and the developing brain: Atypical development*. New York: Guilford.

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. *Behavioral and Brain Functions*, *2*(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. *Behavioral and Brain Functions*, *2*(20).