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Automatic Activation of Internal Magnitudes: A Study of Developmental Dyscalculia

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The association between Arabic numerals and the representations of magnitude in adult developmental dyscalculia was examined. University students compared physical size, vertical positioning (height), or grayness (different shades of gray) of 2 Arabic numerals. The numerical values could produce a Stroop-like numerical congruity effect (NCE; 3–5 vs. 3–5). The dyscalculia group did not show NCE in the grayness task, and their physical comparisons produced a significantly smaller NCE compared with that produced by the control group. Whereas previous research suggested that Arabic numerals activate representations of magnitude automatically, the results of this study indicate that this is not the case because (a) people with developmental dyscalculia require attention to associate internal representations of magnitude with Arabic numerals, and (b) activation of internal magnitudes depends on context (task).

Keywords: Arabic numerals, developmental dyscalculia, magnitude

Developmental dyscalculia (DD; or mathematics disorder in the *Diagnostic and Statistical Manual of Mental Disorders,* American Psychiatric Association, 1994) is a deficit in the processing of numerical and arithmetic information and is associated with neurodevelopmental abnormalities (for a review, see Ardila & Rosselli, 2003; Geary, 2004). Children with DD fail in many numerical tasks, including performing arithmetic operations, solving arithmetic problems, and using numerical reasoning.

Most DD studies are directed to higher level, school-like concepts such as addition and multiplication (Ansari & Karmiloff-Smith, 2002). Accordingly, research is focused on general cognitive functions such as poor working memory span (Bull & Scerif, 2001), deficits in attention systems (Shalev, Auerbach, & Gross-Tsur, 1995), disorder of visuospatial functioning (Bull, Johnston, & Roy, 1999), or deficiency in the retrieval of information (e.g., arithmetic facts) from memory (Kaufmann, Lochy, Drexler, & Semenza, 2004). Such research has several shortcomings. First, the general cognitive functions studied are not specific to numerical processes; they are involved in nonnumerical tasks and skills as well. Second, it has been shown that the most suited method of instruction for children with DD emphasizes basic numerical processes such as the representation of quantities, counting, and so forth (Griffin, Case, & Capodilupo, 1995; Kaufmann, Handl, & Thony, 2003; Perry, 2000). Third, neurofunctional findings show that particular developmental mathematical difficulties involve the parietal lobes.[1] Children with Turner syndrome[2] demonstrate a decrease in brain activity in the parietal lobes or have an abnormal structure of these lobes (Molko et al., 2003). Similarly, Isaacs, Edmonds, Lucas, and Gadian (2001) found that children with very low birth weight who suffer calculation deficits show a reduction in gray matter in the left inferior parietal lobe.

From an empirical perspective, the tasks that are used to diagnose selective deficits in DD frequently incorporate test batteries designed for individuals with brain lesions. These batteries use a pencil-and-paper approach and cannot produce an accurate and detailed analysis of the underlying deficient processes (Ansari & Karmiloff-Smith, 2002; but see, e.g., Geary, Hamson, & Hoard, 2000, who evaluated children with learning disabilities using tests of number comprehension and production, and Koontz & Berch, 1996, who used a computerized numerical version of a stimulus matching task). Hence, the argument of many researchers in the field of DD that this deficit does not include difficulties in basic numerical processes, such as the automatic association of numbers and quantities, should be carefully scrutinized.

In contrast to most DD studies, cognitive neuroscience research on individuals without DD has mainly examined basic numerical processing, such as the mental representations of magnitudes (e.g., Dehaene & Cohen, 1995). Studying basic numerical processing is

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[1] The parietal lobes are considered to be involved in the representation and manipulation of magnitudes (Dehaene & Cohen, 1995). For example, using fMRI, Fias et al. (2003) found that a certain area in the left intraparietal sulcus was responsive specifically to abstract magnitudes. This area was activated when participants compared magnitudes of various stimuli (i.e., angles, lines, and two-digit numbers). In addition, slightly anterior to this site, the authors identified a region involved particularly in number comparison (see also Pinel et al., 2004, who found activation in the right anterior horizontal segment of the intraparietal sulcus during comparisons of physical sizes and numerical dimensions; and Eger et al., 2003, who found that numbers compared with letters and colors activated a bilateral region in the horizontal intraparietal sulcus).

[2] Children with Turner syndrome are characterized by many difficulties, not only those mathematical in nature. We mention the Molko et al. (2003) study because these researchers found parietal damage in these children and suggested the parietal lobe disruption in Turner syndrome may explain the visuospatial and arithmetic impairments that are commonly observed in this syndrome.

especially interesting for two reasons. First, there is strong evidence that infants (e.g., Lipton & Spelke, 2003; Wynn, 1992; Xu & Spelke, 2000) and animals (McComb, Packer, & Pusey, 1994; Nieder, Freedman, & Miller, 2002) possess basic numerical knowledge (such as the ability to process quantities), and thus, this demonstrates that human abilities for number processing have a biological basis[3] (Dehaene, 1997, 2001). Second, it has been suggested that these basic numerical processes underlie higher mathematics (Dehaene, 2001), from which human science and technology is developed.

In view of this state of affairs, we examined the effects of deficits in basic numerical processes (i.e., the automatic association between Arabic numerals and their internal representations of magnitude) in children with DD by using an approach derived from cognitive psychology paradigms that systematically manipulate the numerical stimuli and measure both reaction time (RT) and accuracy. Because the assessment of learning disabilities and methods for improvement require careful analysis of component skills, this work could have important implications both for the teaching of mathematics and for the diagnosis and rehabilitation of people with DD.

Numerical Cognition: The Numerical Congruity Effect

Koontz and Berch (1996) found that children with arithmetic learning disabilities have difficulty *subitizing* (determining the size of a small set of items), which is considered to be an automatic process. In addition, Girelli, Lucangeli, and Butterworth (2000) and Rubinsten, Henik, Berger, and Shahar-Shalev (2002) suggested that certain automatic numerical processes (indicated by the numerical congruity effect; see below) develop with age and with exposure to numbers in school. Tasks that probe automatic processing could help elucidate fundamental difficulties in DD.

In the field of selective attention, many researchers use conflict situations to probe automaticity. To this end, many use the Stroop task or Stroop-like tasks (MacLeod, 1991). In such tasks, participants are presented with two-dimensional stimuli (e.g., a word in color) and asked to focus on one dimension (e.g., the ink color) and ignore the other dimension (e.g., the meaning of the word). In many cases, participants cannot ignore the irrelevant dimension, which interferes with processing of the relevant one. Such a result is considered a failure of selective attention and an indication for the automatic nature of the irrelevant dimension. We used a Stroop-like paradigm to examine how automatic the processing of the numerical dimension is in DD participants.

Imagine that you are presented with two digits having different physical sizes (e.g., 3 and 8) and are asked to pay attention to the physical size and ignore the numerical values. You would probably be faster to respond to congruent trials (in which the physically larger digit corresponds to the larger numerical magnitude, e.g., 3 and 8; response, 8) than to incongruent trials (in which the physically larger digit corresponds to the smaller numerical magnitude, e.g., 3 and 8; response, 3). This effect is called the size congruity effect or, in this article, the *numerical congruity effect* (NCE; Algom, Dekel, & Pansky, 1996; Besner & Coltheart, 1979; Girelli et al., 2000; Henik & Tzelgov, 1982; Pansky & Algom, 1999; Rubinsten et al., 2002; Schwarz & Heinze, 1998; Schwarz & Ischebeck, 2003; Tzelgov, Meyer, & Henik, 1992; Vaid & Corina, 1989). That is, when participants judge the physical sizes of digits, they cannot ignore their numerical values. This NCE indicates that quantities associated with the Arabic graphemes are activated automatically in spite of being irrelevant (for the definition of automaticity, see Carr, 1992; Hasher & Zacks, 1979; Logan, 1985; Posner, Nissen, & Ogden, 1978; Tzelgov, Henik, Sneg, & Baruch, 1996; Zbrodoff & Logan, 1986).

Girelli et al. (2000; see also Butterworth, 1999) found no size congruity effect in the performance of first-grade children when the task was to compare the physical sizes of Arabic numerals and to ignore their numerical values. The NCE emerged only in the third grade and was also significant in the fifth grade. They argued that their findings indicate that children as young as 6 years old do not automatically access the quantitative values of Arabic numerals, as numerical values did not interfere with physical judgments. Rubinsten et al. (2002) recruited participants from the beginning and end of first, third, and fifth grades, as well as university students. They found that the NCE started to appear only at the end of first grade. Accordingly, the authors suggested that the ability to automatically access the quantitative values of Arabic numerals starts only at the end of first grade.

We hypothesized that the ability to automatically or efficiently process the quantities associated with Arabic numerals might be damaged in DD students. These students could be trapped at a particular developmental stage. The comparison of the patterns of their performance and that of elementary schoolchildren (i.e., the results provided in studies by Girelli et al., 2000, and Rubinsten et al., 2002) would point to basic deficiencies in DD. We emphasize, however, that the current work will not enable identification of the source of the damage, that is, whether the deficit is due to a biological mechanism related to number processing (e.g., Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Fias, Lammertyn, & Reynvoet, 2003; Pinel, Piazza, Le Bihan, & Dehaene, 2004) or to problems in the exposure to numbers in school (e.g., Geary, 1995; Newcombe, 2002; Spelke, 2000).

Current Study

We asked students with DD and matched control participants to compare the physical size, height, or grayness of two digits and ignore their numerical values. We included neutral trials to enable examination of the interference and facilitatory components of the NCE. A neutral stimulus was composed of the same digit (e.g., 2

[3] We note, however, that whereas some numerical abilities have a biological basis, as was proposed here, others involve schooling. For example, Spelke (2000) reported an unpublished work by O'Kane and Spelke that demonstrated this point. In the study, the authors asked individuals who were Spanish–English bilingual to memorize all the information presented in two stories that they learned either in English or in Spanish. The authors found that recall of nonnumerical facts, small numbers, or facts about large approximate numerosities was independent of language: Participants who learned in Spanish were equally fast and accurate at retrieving the information when queried in Spanish or in English. In contrast, when participants were tested on large, exact-number facts, they responded more quickly and more accurately when queried in the language in which they learned the story. These findings suggest that information about small numbers and large approximate numerosities is represented by core language-independent systems. On the contrary, large exact numerosities depend on a combination of representations from core systems and the language in which they were studied (for more examples of the influence of learning on number processing, see Geary, 1995; Newcombe, 2002).

and 2) so that the irrelevant dimension (numerical value) was constant. One can compare the neutral stimuli to the incongruent stimuli to examine the interference component, and the neutral stimuli to the congruent stimuli to examine the facilitatory component. We wanted to examine these aspects of the effects because Posner (1978) suggested that facilitation is an indicator of automaticity, whereas interference might reflect attentional processing.

Method

Participants

Thirty-eight students from Ben-Gurion University participated in the experiment. Nineteen of them were diagnosed as having DD, and the other 19 did not have any learning or other disability.

DD group. All the students in this group (14 men and 5 women, *M* age = 24 years, 2 months, *SD* = 1.7) were diagnosed at least once in their past as having DD. They were never diagnosed as having other developmental learning disabilities, such as dyslexia, dysgraphia, or attention-deficit/hyperactivity disorder. We confirmed this diagnosis by using an age-standardized battery of arithmetic tests that are based on the neurocognitive model of arithmetic proposed by McCloskey, Caramazza, and Basili (1985), which was composed by Shalev et al. (2001; see also, Shalev, Manor, Amir, & Gross-Tsur, 1993). We added several items to Shalev et al.'s (2001) battery because of the floor effect. Before the present experiment was run, 41 university students from Ben-Gurion University did all the tests in the battery. This battery of tests is further detailed in Shalev et al.'s study (2001; see also the supplemental materials on the Web at http://dx.doi.org/10.1037/0894-4105.19.5.641.supp and Table 1 in this article). All of the students in the DD group were classified as having DD according to Shalev et al.'s (2001) battery of tests.

For reading assessment, we used a reading test that was composed and published by Shalev et al. (1993) and Shalev, Manor, Auerbach, and Gross-Tsur (1998) and standardized for the purpose of Shalev et al.'s (2001) study. We added several items to Shalev et al.'s (1993, 1998) battery (see Table 2). As with the arithmetic tests, before the present experiment was run, 41 university students from Ben Gurion University did all the reading tests in the battery. We found that our sample of DD students did not have any reading problems and that there were basically no differences in the scores of any one of the reading tests, even in the normal range. We converted participants' scores on the Raven's Progressive Matrices test (Raven, 1996) to IQ scores. Their mean IQ was 110 (*SD* = 16).

Control group. None of the students in this group (14 men and 5 women, *M* age = 23 years, 9 months, *SD* = 2.2) were ever diagnosed as having DD or any other learning disability. All of them took the arithmetic, reading, and Raven's Progressive Matrices tests and did not show any learning disability. Their mean IQ score was 111 (*SD* = 11).

Stimuli and Design

Each trial was composed of two digits such that one digit appeared on each side of the center of the computer screen. Each participant performed three kinds of comparisons in three separate blocks. In the first, the relevant dimension was physical size; in the second, height (vertical position); and in the third, grayness. In every block there were 432 different stimuli. Within the set of stimuli prepared for the size, height, or grayness comparisons, each digit and each physical size appeared on both sides of the visual field an equal number of times (hence there was a total of 864 trials in each block). Each block contained equal numbers of congruent, incongruent, and neutral stimuli. A congruent stimulus was defined as a pair of digits in which a given digit was larger on both the relevant and irrelevant dimensions (e.g., 5 3 in the size comparison, $^{5}\ _{3}$ in the height comparison, and 5 3 in the luminance comparison). A neutral stimulus was defined as a pair of digits that differed only on the relevant dimension (e.g., 5 5 in the size comparison, $^{5}\ _{5}$ in the height comparison, and 5 5 in the luminance comparison). An incongruent stimulus was defined as a pair of digits in which a given digit was simultaneously larger on one dimension and smaller on the other (e.g., 3 5 in the size comparison, $^{3}\ _{5}$ in the height comparison, and 3 5 in the luminance comparison). The digits 1 through 9 were used, with the digit 5 excluded. The two digits in each pair could be of the same numerical value (in which case the pair served as a neutral for size, height, and luminance comparisons) or could differ in numerical

Table 1
Arithmetic Scores (Mean Number of Errors) of Developmental Dyscalculia and Control Groups

	Developmental dyscalculia		Control		
Arithmetic score	*M* errors (*SD*)	Score with relation to population	*M* errors (*SD*)	Score with relation to population	Comparison (*p*)
Number facts (no. of tasks)					
Addition (5)	0.05 (0.28)	Intact	0.04 (0.14)	Intact	*ns*
Subtraction (5)	0.06 (0.34)	Intact	0.03 (0.19)	Intact	*ns*
Multiplication (5)	1.10 (0.54)	Below standard	0.10 (0.23)	Intact	<.001
Division (5)	0.80 (0.73)	Below standard	0.25 (0.28)	Intact	<.01
Complex arithmetic (no. of tasks)					
Addition (8)	0.81 (0.21)	Intact	0.75 (0.19)	Intact	*ns*
Subtraction (8)	1.30 (0.19)	Below standard	0.55 (0.24)	Intact	<.01
Multiplication (8)	2.90 (2.10)	Below standard	1.30 (1.60)	Intact	<.05
Division (8)	5.10 (3.30)	Below standard	1.50 (2.80)	Intact	<.001
Decimals (no. of tasks)					
Addition (4)	1.80 (1.80)	Below standard	0.90 (2.10)	Intact	<.05
Subtraction (4)	2.10 (1.30)	Below standard	1.0 (2.20)	Intact	<.01
Fractions (no. of tasks)					
Addition (5)	2.10 (1.80)	Below standard	0.65 (1.30)	Intact	<.001
Subtraction (5)	2.30 (1.50)	Below standard	1.30 (0.60)	Intact	<.01
Multiplication (5)	2.40 (1.70)	Below standard	0.80 (1.10)	Intact	<.001
Division (5)	2.40 (2.30)	Below standard	1.20 (1.40)	Intact	<.001

Note. The results of Part 1 of the arithmetic battery (number comprehension and production) are not presented in this table because all these scores were intact and there was no significant difference between the two groups. The score of each participant was compared with the age and education standardized scores.

Table 2
Reading Scores (Mean Number of Errors) of Developmental Dyscalculia and Control Groups

Reading score	Developmental dyscalculia *M* errors (*SD*)	Developmental dyscalculia Score with relation to population	Control *M* errors (*SD*)	Control Score with relation to population	Comparison (*p*)
Reading comprehension (no. of tasks)					
Words (15)	0.01 (0.11)	Intact	0.02 (0.14)	Intact	*ns*
Synonyms (15)	0.03 (0.14)	Intact	0.03 (0.15)	Intact	*ns*
Text (3)	0.10 (0.48)	Intact	0.15 (0.33)	Intact	*ns*
Reading production (no. of tasks)					
Words (15)	0.77 (0.21)	Intact	0.75 (0.19)	Intact	*ns*
Words (RT)	632 (139)	Intact	521 (193)	Intact	*ns*
Nonwords (15)	1.20 (1.80)	Intact	1.30 (1.60)	Intact	*ns*
Nonwords (RT)	624 (145)	Intact	597 (119)	Intact	*ns*
Text (2)	0.02 (3.90)	Intact	0.04 (3.80)	Intact	*ns*
Phonological awareness (46 tasks)	0.04 (2.70)	Intact	0.05 (2.40)	Intact	*ns*

Note. RT = reaction time.

distance. There were three numerical distances: 1 (the digits 1–2, 3–4, 6–7, 8–9), 2 (the digits 1–3, 2–4, 6–8, 7–9), or 5 (the digits 1–6, 2–7, 3–8, 4–9). Accordingly, each distance included four different pairs of digits.

For each one of the size, height, or grayness dimensions, we used eight different stimuli that created a set similar to the set of the numerical stimuli (see supplemental materials on the Web at http://dx.doi.org/10.1037/0894-4105.19.5.641.supp for further details). We chose these specific size, height, and luminance levels because they created a semilogarithmic function similar to numbers (Dehaene, 1989). In a previous experiment (with different participants), all of the chosen stimuli for the different numerical, luminance, and size distances were matched on participants' RTs. Hence, it can be argued that the numerical stimuli were as salient as the other dimensional stimuli (Cohen-Kadosh & Henik, 2004). The use of RT to match various dimensions was recently suggested by Melara and Algom (2003). Therefore, there were eight different sizes (i.e., height of the printed Arabic numeral), heights (i.e., height of presentation compared with fixation point), or grayness levels (i.e., levels of photometric luminance measured in cd/m^2 units), which were used to create 12 different pairs with three different size, height, or grayness distances (distances of 1, 2, or 5).

In short, each block of the three comparisons had 27 different possible conditions (three distances of physical sizes, three distances of numerical values, and three congruency conditions). Each condition had 32 trials (4 different stimuli for each numerical distance $\times$ 4 different stimuli for each physical distance $\times$ 2 sides of the target digit) for a total of 864 trials per block. Fifty-four practice trials preceded each one of the three experimental blocks. (See supplemental materials on the Web at http://dx.doi.org/10.1037/0894-4105.19.5.641.supp for further details.)

In each one of the blocks, the following variables were manipulated: group (DD vs. control); task (size, height, or luminance); distance of physical size, height, or luminance in the relevant task (distance of 1, 2, or 5); numerical distance (1, 2, or 5); and congruity (incongruent, neutral, or congruent). Thus, we had a $2 \times 3 \times 3 \times 3 \times 3$ factorial design. Group was the only between-participants variable, and task was manipulated within participants but between blocks.

Procedure

Participants were asked to decide, as quickly as possible and avoiding errors, which of two digits was superior (i.e., most suitable for the question asked). They indicated their decision by pressing the key corresponding to the appropriate side of the display. We measured RT and error rates.

Each trial began with a fixation point presented for 300 ms. Five hundred ms after the fixation point was eliminated, a pair of digits appeared and remained in view until the participant pressed a key (but not for more than 5,000 ms). A new stimulus appeared 1,500 ms after response onset.

Results

Error rates were generally low (the DD group had 1.8%, 2.2%, and 2.5% of errors in the size, height, and grayness tasks, respectively; the control group had 1.6%, 2.4%, and 2.6% of errors in the size, height, and grayness tasks, respectively) and therefore were not analyzed.

For every participant in each condition, the mean RT was calculated (only for correct trials). These means were subjected to a five-way analysis of variance, with group as the only between-participants factor and task, distance (according to the task), numerical distance, and congruity as within-participant factors.

Four main effects were significant. Responding was faster in the control group, (M RT = 596 ms, SD = 112 ms), $F(1, 35) = 268$, $MSE = 2{,}505{,}149$, $p < .001$, compared with that of the DD group (M = 779 ms, SD = 163 ms). Physical distances (i.e., size, height, and luminance distances) were fastest for distances of five units (M = 726 ms, SD = 117 ms), slower for two units (M = 687 ms, SD = 132 ms), and slowest for one unit (M = 650 ms, SD = 141 ms), $F(2, 70) = 62.7$, $MSE = 140{,}311$, $p < .001$. Similarly, participants responded faster to larger numerical distances than to smaller ones (for one unit, M RT = 710 ms, SD = 164 ms; for two units, M = 684 ms, SD = 143 ms; and for five units, M = 669 ms, SD = 119 ms), $F(2, 70) = 51.5$, $MSE = 44{,}977$, $p < .001$. There was a significant congruity effect, $F(2, 70) = 56.9$, $MSE = 14{,}431$, $p < .001$, with mean RTs of 736 ms (SD = 169 ms), 677 ms (SD = 146 ms), and 656 ms (SD = 127 ms) for incongruent, neutral, and congruent pairs, respectively. The interaction between task, physical distance (i.e., size, height, or luminance distances), and numerical distance was significant, $F(8, 280) = 3.9$, $MSE = 26{,}136$, $p < .001$.

The interaction between group, task, and congruity, $F(4, 140) = 2.5$, $MSE = 641{,}875$, $p = .051$, is presented in Figure 1. We proceeded with analyses for each task separately (Keppel, 1991).

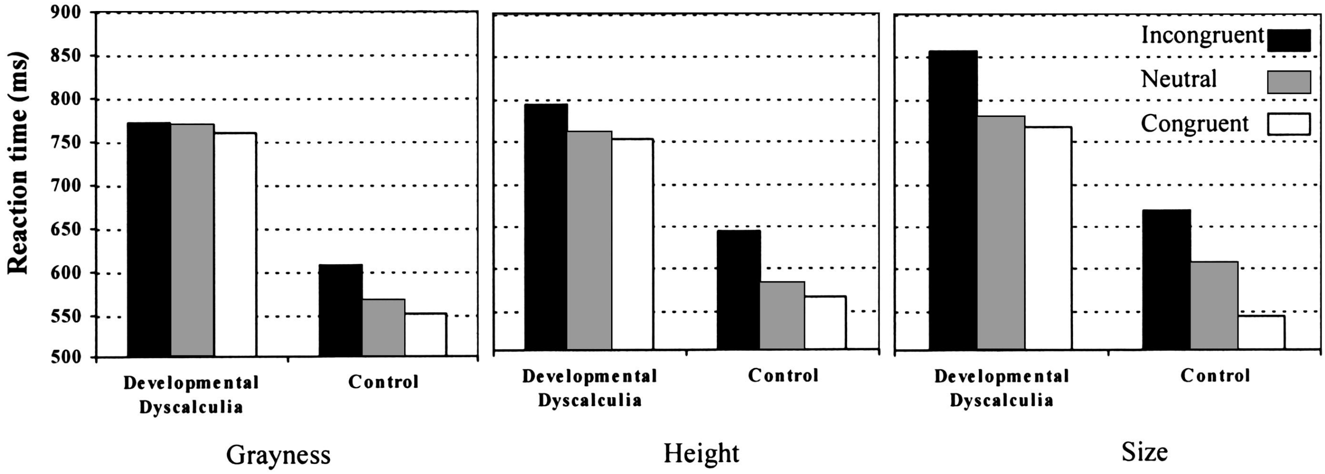

Figure 1. The Congruity × Task × Group interaction.

Grayness Comparisons

As can be seen in Figure 1, the congruity effect appeared only in the control group. Accordingly, the interaction between congruity and group was significant, $F(2, 72) = 7.3$, $MSE = 125{,}576$, $p <$ .001. The main effect of congruency was not significant in the DD group. In contrast, it was significant in the control group, $F(2, 36) = 33.4$, $MSE = 501{,}609$, $p < .0001$, and was composed of only an interference component (incongruent vs. neutral), $F(1, 18) = 39.9$, $MSE = 640{,}467$, $p < .0001$.

Height Comparisons

The interaction between congruity and group was significant, $F(2, 72) = 4.3$, $MSE = 448{,}576$, $p < .05$; the DD group produced a nonsignificant NCE (incongruent vs. congruent), $F(1, 18) = 6.1$, $MSE = 40{,}711$, $p = .067$, that was due to a nonsignificant interference component (incongruent vs. neutral), $F(1, 18) = 5.9$, $MSE = 40{,}747$, $p = .063$. The control group produced an NCE, $F(1, 18) = 12.2$, $MSE = 30{,}540$, $p < .001$, that was also composed of an interference component, $F(1, 18) = 9.05$, $MSE = 153{,}056$, $p < .01$. Both the congruity effect and the interference component were significantly larger in the control group than in the DD group, $F(1, 36) = 8.6$, $MSE = 202{,}292$, $p < .01$; and $F(1, 36) = 10.9$, $MSE = 173{,}316$, $p < .001$, for the congruity and interference effects, respectively.

Size Comparisons

The interaction between congruity and group was nonsignificant, $F(2, 72) = 3.6$, $MSE = 59{,}449$, $p = .08$. The congruity effect was significant in both groups, $F(2, 36) = 14.4$, $MSE = 634{,}053$, $p < .0001$; and $F(2, 36) = 10.8$, $MSE = 639{,}753$, $p < .0001$, for the DD and the control groups, respectively. Note, however, that whereas the DD group showed only an interference component, $F(1, 18) = 27.29$, $MSE = 8{,}329{,}441$, $p < .001$, the control group showed both interference and facilitation, $F(1, 18) = 36.1$, $MSE = 8{,}444$, $p < .001$; and $F(1, 18) = 65$, $MSE = 334{,}469$, $p <$ .001, respectively. Moreover, the NCE and interference component were larger in the control group compared with the DD group, $F(1, 36) = 5.6$, $MSE = 578{,}333$, $p = .054$; and $F(1, 36) = 4.1$, $MSE = 31{,}466$, $p = .06$, respectively.

Comparisons Between Tasks

In the control group, both the NCE and the interference component were significantly larger in the height task than in the grayness task, $F(1, 18) = 9.9$, $MSE = 14{,}639$, $p < .01$; and $F(1, 18) = 10.1$, $MSE = 16{,}745$, $p < .001$, respectively, and significantly larger in the size task than in the height task, $F(1, 18) = 8.5$, $MSE = 89{,}861$, $p < .05$. In contrast, in the DD group only the interference component of the size task was significantly larger than the one in the height task, $F(1, 18) = 8.1$, $MSE = 245{,}785$, $p < .05$.

Discussion

Let us summarize the main results.

1. In the control group, the NCE (i.e., the difference in RT between congruent and incongruent trials) was the smallest when the task was to decide which one of the digits was darker, and it was the largest when the task was to decide which one of the digits was physically larger. In the grayness and height tasks, the congruity effect was composed only of the interference component (i.e., the difference in RT between incongruent and neutral trials), whereas the size task showed both interference and facilitation.
2. In contrast, the DD group showed no congruity effect in the grayness task. In addition, in the height and physical size tasks the numerical congruity was composed of the interference component only. Moreover, the effect was smaller than the one found in the control group for the same tasks.
3. All of the chosen stimuli for the different numerical, luminance, and size distances were matched on participants' RTs (Cohen-Kadosh & Henik, 2004). Using RT to match various dimensions, in particular with respect to a Stroop-like situation, was recently suggested by Melara

and Algom (2003). As a result, the numerical stimuli were as salient as the other dimensions, and no significant difference was found in RTs of the three different tasks.

Before further discussion of our results, we note that no significant difference between the DD and control groups was found on the scores of Part 1 of the arithmetic battery, that is, the number comprehension and production part. This also fits in with previous studies that have found "that the basic numerical competencies (e.g., identifying Arabic numerals, comparing the magnitudes of numbers) of most children with mathematical learning disabilities, though often delayed, are largely intact, at least for the processing of simple numbers" (Geary, 2004, p. 5). As we argued previously, the tasks used to diagnose selective deficits in DD frequently use test batteries that use a pencil-and-paper approach and cannot produce an accurate and detailed analysis of the underlying deficient processes (Ansari & Karmiloff-Smith, 2002). Hence, it is very interesting to note that when using such pencil-and-paper batteries, no difficulty is found in the ability of students with DD to process simple numbers and magnitudes (even in the present experiment). However, when we used an approach derived from cognitive psychology paradigms that systematically manipulated the numerical stimuli and measured both RT and accuracy, it was clear that the DD group had a problem with some aspects of simple number processing.

In the DD group, numerical congruity and the interference component were always smaller compared with those of the control group. However, we note that there are certain features that were similar to the control group. The numerical congruity and the interference effects were smallest when the task was to decide which one of the digits was darker (actually there was no effect at all), and they were the largest when the task was to decide which one of the digits was larger. These results suggest that the people in the DD group had an intact internal representation of magnitude. If the internal representation of magnitude had been damaged, no NCE could have appeared in any one of the tasks; moreover, it would not have varied among tasks. In addition, this group was able to attend to various features of magnitude. This is indicated by the fact that the effect was largest in the size task and smallest in the grayness task.

We suggest that only when attending to features that characterize magnitude are the internal representations of magnitude activated more easily or more automatically. However, it might also be possible that participants focus their attention on one dimension (e.g., grayness) without getting much interference from the other dimension (e.g., numerical value), even if the numerical dimension is strongly activated. This last argument is supported by Pinel et al. (2004), who tested only nonimpaired individuals who were similar to our control group. They found the same pattern of behavioral results: a robust interference between number and size and smaller interference between number and luminance. The authors tried to identify the cerebral substrates of a possible convergence between processing streams for number and size on the one hand, and for size and luminance on the other, by using functional MRI. They found activation in the right anterior horizontal segment of the intraparietal sulcus (HIPS) during comparisons of physical size, with a size distance effect comparable to the numerical distance effect (see also Dehaene, Piazza, Pinel, & Cohen, 2003). In addition, they found an overlap between the distance effects for luminance and physical size in a set of bilateral occipitotemporal and posterior intraparietal regions. The authors argued that the observed occipitotemporal activations reflect an attentional amplification of the relevant perceptual factor (i.e., luminance and size) within the extrastriate visual cortex. According to their findings, our results might be explained in the following way: Because the dimensions (i.e., numerical values and shades of gray) involve different cortical regions, it may be possible for the DD participants to focus their attention on one dimension (i.e., grayness) and to accrue evidence for their motor decisions, without getting much interfering evidence from the other dimension (i.e., numerical value), even if it is strongly activated. In such a case, the DD group might be damaged in its ability to focus attention on one dimension. This explanation does not fit well with our findings, for three reasons. First, if attention was damaged, then size congruity, and especially the interference component, would not vary among tasks. Second, Pinel et al. (2004) found activation in the HIPS during comparisons of both physical size and numerical value, with a size distance effect comparable to the numerical distance effect. Accordingly, these two dimensions share the same cortical region, and when participants focus attention on one dimension (i.e., size), the other irrelevant dimension (i.e., numerical) should be activated, and the interference component should appear. However, we found that the interference component was reduced in the size task. Third, the participants with DD had mathematical problems and did not have any attention problems. Hence, the reduced interference is most likely to reduced quantity activation and not to focus of attention problems.

So, why is the effect smaller in the DD group compared with the control group? We suggest that people with DD have problems automatically associating internal representation of magnitude to Arabic numerals. The idea that people with DD might have deficits in automatic processing related to numbers is not new. As we mentioned in the introduction, Koontz and Berch (1996) found that for children with DD, the subitizing range (i.e., automatically determining the magnitude of a small number set) may be smaller than that of the control group.

Contrary to the control group, the DD group showed no facilitation component (i.e., congruent vs. neutral) in all three tasks. That is, the NCE was composed only of the interference component. Several reports have suggested dissociation between the interference and the facilitatory components of the Stroop effect (Lindsay & Jacoby, 1994; Posner, 1978; Tzelgov, Henik, & Berger, 1992). The facilitatory component is supposed to involve processes that are more automatic because they are less subject to strategic control (e.g., see Tzelgov et al., 1992). As was mentioned previously, Posner (1978) suggested that facilitation is an indicator of automaticity, whereas interference might reflect attentional processing. Accordingly, in the DD group the ability to automatically associate Arabic numerals with their internal representation of magnitude is not fully automatic even when attending to features that characterize magnitude (e.g., size).

No NCE appeared when the DD group was asked to decide which one of the digits was darker. The same pattern of results appeared with participants at the beginning of first grade who were asked to decide which one of two digits was larger (Rubinsten et al., 2002). We suggested that both maturation and schooling are required in order for the digits–magnitude associations to develop. Accordingly, it is possible that both neuroanatomical and practice factors might have led to the disconnection or weak connections between Arabic numerals and internal magnitudes in the DD group. This suggestion is also supported by findings that some numerical abilities have a biological basis (e.g., Eger et al., 2003; Fias et al., 2003; Pinel et al., 2004), and others are school taught (e.g., Geary, 1995; Newcombe, 2002; Spelke, 2000). If this last suggestion is correct, then (a) practice might improve the ability of Arabic numerals to activate internal magnitudes (Hasher & Zacks, 1979; Shiffrin & Schneider, 1977), and (b) the developmental dysfunction in DD needs to be further explored, especially in light of controversial results (e.g., Gross-Tsur, Shalev, Manor, & Amir, 1995; PeBenito, Fisch, & Fisch, 1988; Weintraub & Mesulam, 1983).

The pattern of numerical congruity in the size task (in the DD group) is similar to the one found with children at the end of first grade (Rubinsten et al., 2002); it includes only the interference component. We argued that schooling and probably maturation of the cognitive system improve the ability to access the internal magnitudes, but this access is still not fully automatic at the end of first grade. What we show here is that in the DD group, the NCE can be larger simply by asking, “Which stimulus is larger?” instead of “Which is darker?” Directing attention to magnitude features such as size enlarges the numerical congruity effect. Thinking of size rather than of grayness helps the DD group in associating magnitudes with digits, just as maturation and schooling factors help students in first grade. Yet, it should be remembered that the NCE in the DD group resembles the one appearing in students at the end of first grade and not the one appearing in university students without DD.

Conclusions

The current work reveals a basic difficulty that might lead to many other mathematical problems found in students with DD. Our results point to the fact that people with DD have problems in the automatic activation of magnitudes by digits. We also showed that Arabic numerals do not always automatically (at least not fully automatically) activate their internal magnitudes (e.g., in the case of the grayness task) even in the non-DD population. Because assessing learning and improving learning methods requires careful task analysis at the level of component skills, these results might have implications for the instruction of mathematics and for the diagnosis and rehabilitation of DD. It might be, for example, that because people with DD have problems in automatically associating magnitudes with digits, intensive practice in associating magnitudes with their Arabic numerals (Griffin et al., 1995; Hasher & Zacks, 1979; Logan, 1988) might help in the rehabilitation of DD.

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