Journal of Educational Psychology
2006, Vol. 98, No. 4, 854–867

0022-0663/06/$12.00 DOI: 10.1037/0022-0663.98.4.854

Double Dissociation of Functions in Developmental Dyslexia and Dyscalculia

Orly Rubinsten and Avishai Henik
Ben-Gurion University of the Negev

This work examines the association between symbols and their representation in adult developmental dyscalculia and dyslexia. Experiment 1 used comparative judgment of numerals, and it was found that in physical comparisons (e.g., 3–5 vs. 3–5) the dyscalculia group showed a significantly smaller congruity effect than did the dyslexia and the control groups. Experiment 2 used Navon figures (D. Navon, 1977) in Hebrew, and participants were asked to name the large or the small letters. Phoneme similarity modulated performance of the control and the dyscalculia groups and showed a very small effect in the dyslexia group. This suggests that the dyscalculia population has difficulties in automatically associating numerals with magnitudes but no problems in associating letters with phonemes, whereas the dyslexia population shows the opposite pattern.

Keywords: developmental dyslexia, developmental dyscalculia, phonemes, quantities

Throughout the evolution of human culture, written symbols such as digits and letters have been developed for broadening channels of communication. The written system is a unique achievement of the human species, which has enabled the development of human technology and science. Yet, by the end of the 19th century, cases of children and adults with difficulties in writing had already been observed (e.g., Hinshelwood, 1917; Morgan, 1896; Orton, 1937), and by the end of the 20th century, cases of children and adults with problems in calculation (Steeves, 1983) had been described. These phenomena are traditionally called *developmental dyslexia* and *dyscalculia*.

It has been shown that during the first years of life children make rapid progress toward becoming competent symbol users (DeLoache, 2004). In this article, we aim to understand the relation between the development of symbolic competence in different symbolic domains, that is, digits and letters. Specifically, we are interested in determining whether a difficulty in one domain also appears in the other.

Developmental Dyslexia

Children with developmental dyslexia show an inconsistency between reading abilities and intelligence. Today, it is a well-accepted fact that dyslexia is a neurological disorder with a lifelong resistance, that is, it continues into adulthood. The phonological theory postulates that children suffering from dyslexia have a specific impairment in the representation, storage, or retrieval of speech sounds (phonemes). Because reading requires learning the grapheme–phoneme correspondence, that is, the association between letters and elementary sounds of speech, a poor representation, storage, or retrieval of the appropriate sounds jeopardizes the ability to read (Bishop & Adams, 1990; Bradley & Bryant, 1983; Castles & Coltheart, 2003; Goswami, 2003; for a review see McCandliss & Noble, 2003; S. E. Shaywitz, 2003; Snowling, 1991; Stanovich, 1988). However, see for example, Bailey, Manis, Pedersen, and Seidenberg (2004), Castles and Coltheart (1993), and Stanovich, Siegel, and Gottardo (1997), for a discussion about subtypes of developmental dyslexia.

A case has also been made for impairment in the brain's visual mechanisms of reading as a possible contributing factor in developmental dyslexia, leading to the magnosystem hypothesis. The reduced visual magnocellular sensitivity of some people suffering from dyslexia may cause poor eye control and this limits their ability to acquire, in particular, orthographic skills (e.g., Jenner, Rosen, & Galaburda, 1999; Stein, 2001; Stein & Walsh, 1997). Finally, one interpretation of available evidence points to dyslexia as a multisystem deficit, possibly based on a fundamental incapacity of the brain to perform tasks requiring processing of brief stimuli in rapid temporal succession (e.g., Gelfand & Bookheimer, 2003; Poldrack et al., 2001). However, it should be noted that even those theories that object to the phonological theory do not question the existence of a phonological deficit and its contribution to reading problems. Hence, these theories argue that the phonological deficit is just one feature of dyslexia and that the disorder extends to general sensory, motor, or learning processes (e.g., Facoetti et al., 2003; Ramus, 2001, 2003). In addition, a greater genetic contribution was found in children suffering from phonological dyslexia compared with surface dyslexia (i.e., people with particular difficulty in reading irregular words; see, e.g., Castles, Datta, Gayan, & Olson, 1999).

Because of their deficits, people suffering from dyslexia perform poorly on tasks requiring phonological awareness, that is, conscious segmentation and manipulation of speech sounds. The

Orly Rubinsten and Avishai Henik, Department of Behavioral Sciences and Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev, Beer-Sheva, Israel.

We thank Ruth Shalev and her colleagues for allowing us to use their age-standardized battery of arithmetic and reading tests.

Correspondence concerning this article should be addressed to Orly Rubinsten, Department of Behavioral Sciences, Ben-Gurion University of the Negev, Beer-Sheva, 84105 Israel. E-mail: orlyr@bgumail.bgu.ac.il

common argument, which is focused on the phoneme level, is that phonological awareness is important for the acquisition of early reading skills. Given that letters typically represent individual phonemes, a child needs to be aware of the phonemic parts in spoken words before learning the rules of grapheme–phoneme correspondence (e.g., Wagner & Torgesen, 1987). On the other hand, in their review article Castles and Coltheart (2003) argued that it might be that

> . . .once children acquire reading and spelling skills, they change the way in which they perform phonological awareness tasks, using their orthographic skills, either in addition to or instead of their phonological skills, to arrive at a solution. So, on this account, the ability to perceive and manipulate the sounds of spoken language does not assist literacy acquisition, nor does the acquisition of reading and spelling ability affect phonological awareness. Rather, the association between the two arises because both are, to a greater or lesser degree, indices of orthographic skill (p. 95; see also Share, 1995; Share & Stanovich, 1995).

Accordingly, it might be very interesting to determine whether people that do have deficits in phonological awareness tasks but have had many years of practice with grapheme to phoneme connections might still have problems in this domain, that is, in their ability to relate graphemes to phonemes is not fully automatic or efficient.

It should be noted that although the phonological theory suggests that people suffering from dyslexia have problems in their ability to associate phonemes with their representative letters, research has been mainly directed to phonological awareness and less to the ability to automatically associate letters with phonemes (but see, e.g., Castles & Coltheart, 2003; McCandliss & Noble, 2003; B. A. Shaywitz et al., 2002). We examine whether adults suffering from developmental phonological dyslexia, who have had many years of practice with reading, have deficits in the ability to automatically associate letters with phonemes.

Developmental Dyscalculia

Developmental dyscalculia (or mathematics disorder in the *Diagnostic and Statistical Manual of Mental Disorders;* 4th ed.; American Psychiatric Association, 1994) is a deficit in the processing of numerical and arithmetical information and is associated with neurodevelopmental abnormalities (for a review see Ardila & Rosselli, 2003; Geary, 2004). Children suffering from developmental dyscalculia fail in many numerical tasks, including performing arithmetical operations, solving arithmetical problems, and using numerical reasoning. Most of the developmental dyscalculia studies have been directed to higher level, school-like concepts such as addition and multiplication (Ansari & Karmiloff-Smith, 2002). Accordingly, research has focused on general cognitive functions like poor working memory span (Bull & Scerif, 2001), disorders 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). From an empirical perspective, the tasks that are used to diagnose selective deficits in developmental dyscalculia frequently use test batteries designed for individuals with brain lesions. These batteries use a pencil-and-paper approach, which makes it difficult to produce an accurate and detailed analysis of the underlying deficient processes (Ansari & Karmiloff-Smith, 2002; but see, e.g., Geary, Hamson, & Hoard, 2000; and Koontz & Berch, 1996, who used a computerized numerical version of a stimulus matching task). Hence, the argument of some researchers in the field of developmental dyscalculia that this deficit does not include difficulties in basic numerical processes (e.g., Ansari & Karmiloff-Smith, 2002; Bull et al., 1999; Bull & Scerif, 2001), such as the automatic association of numbers and quantities, should be carefully scrutinized.

Recently, Rubinsten and Henik (2005) used an approach derived from cognitive psychology. They used a conflict situation (i.e., Stroop-like task) and asked participants to compare physical sizes of digits and to ignore their numerical values (e.g., for 3 8, the physically larger digit is 3). Whereas the control group produced the regular numerical congruity effect—longer reaction times (RTs) to incongruent than to congruent stimuli (Algom, Dekel, & Pansky, 1996; Besner & Coltheart, 1979; Girelli, Lucangeli, & Butterworth, 2000; Henik & Tzelgov, 1982; Pansky & Algom, 1999; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Schwartz & Ischebeck, 2003; Schwarz & Heinze, 1998; Tzelgov, Meyer, & Henik, 1992; Vaid & Corina, 1989), the dyscalculia group produced a significantly smaller effect. This suggests that people suffering from developmental dyscalculia have difficulties in automatically associating internal representations of magnitude with Arabic numerals (see also Girelli et al., 2000; Landerl, Bevan, & Butterworth, 2004). This suggestion is supported by neurofunctional findings, which point to a strong connection between developmental dyscalculia and deficits in processing basic numerical information. It has been shown that particular developmental mathematical difficulties involve the parietal lobes.[1] Children with Turner Syndrome 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. It seems that people suffering from developmental dyscalculia do not associate magnitudes with written digits automatically. The question is whether this is a general problem; that is, do these people have problems in associating any written symbol with its mental representation?

The Present Research

The purpose of the present article is to determine whether people suffering from developmental learning disabilities have a

[1] The parietal lobes are considered to be involved in the representation and manipulation of magnitudes (Cohen Kadosh et al., 2005; Dehaene & Cohen, 1995). For example, by using fMRI Fias, Lammertyn, and Reynvoet (2003) found that a certain area in the left intraparietal sulcus was specifically responsive to abstract magnitudes. This area was activated when participants compared magnitudes of various stimuli (i.e., angles, lines, two-digit numbers). In addition, slightly anterior to this site the authors identified a region particularly involved in number comparison (see also Eger et al., 2003, who found that numbers compared with letters and colors activated a bilateral region in the horizontal intraparietal sulcus; and 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).

general difficulty in automatically associating symbols with their mental representations, or is this difficulty specific to letters in the case of dyslexia and to digits in the case of dyscalculia. Notice that several researchers have already argued that people with dyslexia have problems in the automaticity of reading. However, they defined *automaticity* as the speed with which a range of stimuli (i.e., words) is processed (Nicholson & Fawcett, 1990; Raberger, 2003; Wolff, 2002; Wolff, Michel, & Ovrut, 1990; Wolff, Michel, Ovrut, & Drake, 1990; Yap & Van Der Leij, 1994). Generally, people suffering from learning disabilities, both developmental dyscalculia and dyslexia, show slower reaction times (e.g., Koontz & Berch, 1996; Rubinsten & Henik, 2005; S. E. Shaywitz, 2003). For example, they are both slower compared with controls in the numerical Stroop task. Hence, studying general slowness in dyscalculia and in dyslexia has several shortcomings. First, it cannot help in differentiating between these two groups. Second, general slowness is involved in nonnumerical and nonphonological tasks as well. Accordingly, by using an approach derived from cognitive psychology paradigms (e.g., Stroop) that examine implicit processing (i.e., automatic processing), the mental processes that distinguish between these two groups can appear. Hence, contrary to research that defines automaticity as the speed of processing, we examine a more extreme version of automaticity; the presentation of implicit processing of irrelevant information (Tzelgov, Henik, Sneg, & Baruch, 1996). We were able to achieve this end by using two different paradigms that separately examine implicit processing of either sounds of speech or numerical values.

In the first experiment, we used a Stroop-like paradigm with one block in which the numerical values of the digits were irrelevant to the participant's decision concerning the physical sizes of the digits and with the other block in which the physical sizes of the digits were irrelevant to the participant's decision concerning the numerical values of the digits. This paradigm enabled us to test the ability of our participants (with developmental dyslexia and dyscalculia) to automatically associate digits with magnitudes. We hypothesized that the ability of students suffering from developmental dyscalculia (compared with students with developmental dyslexia and controls) to automatically or efficiently process quantities associated with Arabic numerals might be damaged. The students with developmental dyscalculia could be trapped at a particular developmental stage. The comparison of the patterns of their performance and that of elementary school children (i.e., results provided in Girelli et al., 2000; Rubinsten et al., 2002) would point to basic deficiencies in developmental dyscalculia.

In the second experiment we used Navon figures (Navon, 1977; Robertson, Lamb, & Zaidel, 1993), in which single Hebrew letters (i.e., global) were written or built up of smaller letters (i.e., local) that sound the same (i.e., a "same sound" trial; e.g., the Hebrew letter ת that sounds like /t/ was written with small letters of ט that sound also like /t/; see Figure 1) or of letters that sound different (i.e., a "different sound" trial; e.g., the Hebrew letter ת that sounds like /t/ was written with small letters of ק that sound like /k/; see Figure 1). The participant's task was to name either the large letter (global) and to ignore the composite small letters or, in a different block, to name the small letters (local) and to ignore the large letter. If participants have problems in automatically associating letters with phonemes, then the presentation of two different letters having the same phoneme might not interfere with their naming (because each letter is not strongly or automatically associated with its own phoneme). In contrast, if they have no deficit in associating letters with their phonemes, that is, each letter is strongly or automatically associated with its own phoneme, then the presentation of two different letters with the same phoneme will interfere with their naming.

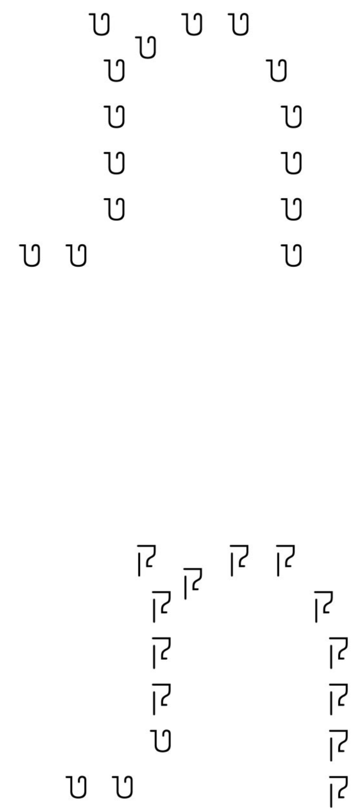

Figure 1. Example of stimuli in Experiment 2.

It should be noted that the present research is important to both cognitive theories of normal processing and to the field of learning disabilities. Because the assessment of learning disabilities and methods for improvement of such disabilities require careful analysis of component skills (Ansari & Coch, 2006; Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001), this work could have important implications both for the teaching of reading and mathematics and for the diagnosis and rehabilitation of people with learning disabilities.

Experiment 1

This experiment examines distance and numerical congruity effects with dyscalculia, dyslexia, and control groups. We asked our participants to compare digits that varied in both numerical and physical dimensions. The participants evaluated (in different blocks) the physical size or the numerical value of digits. We used three numerical distances: 1 (e.g., *2–3*), 2 (e.g., *2–4*), and 5 (e.g., *2–7*). Numerical distance was manipulated independently of the congruence between the physical and numerical dimensions of the stimuli.

We also examine the interference and facilitatory components of the numerical congruity effect by using neutral conditions. In a neutral stimulus, the irrelevant dimension does not interfere or facilitate the decision. We wanted to examine interference and facilitation because Posner (1978) suggested that facilitation is an indicator of automaticity, whereas interference might reflect more attentional processing.

Note that in this paradigm, especially in the numerical decision task (i.e., deciding which one of two presented digits is numerically larger while ignoring their physical sizes), the *distance effect* might appear, that is, the larger the numerical difference between two digits, the shorter the time required to decide which digit is larger (Moyer & Landauer, 1967). For example, it takes longer to decide that 8 is larger than 6 than to decide that 8 is larger than 1. This distance effect has been reported in numerous studies (e.g., Dehaene, 1989; Dehaene, Dupoux, & Mehler, 1990; Duncan & McFarland, 1980; Henik & Tzelgov, 1982; Moyer & Landauer, 1967; Schwarz & Heinze, 1998; Tzelgov, Meyer, et al., 1992). It has been postulated that the source of the distance effect is the overlap between representations of numbers. That is, the internal semantic representations of close numbers, such as 1 and 2, overlap more than those of more distant numbers (Dehaene & Akhavein, 1995; Gallistel & Gelman, 1992).

Method

Participants

Fifty-one students from Ben-Gurion University of the Negev participated in the experiment. All were native Hebrew speakers and were paid for participating in the experiment. Seventeen of them were diagnosed as having developmental dyscalculia, 17 were diagnosed as suffering from developmental dyslexia, and the other 17 were the control group. It should be noted that all the participants (not including the control group) suffered either from developmental dyscalculia or developmental dyslexia but not from both; that is, double deficit individuals were excluded.

The developmental dyscalculia group. All the students in this group (14 men, among whom 12 were right handed, and 3 women, all of whom were right handed; age: $M = 23.9$ years, $SD = 2.1$) were diagnosed at least once in their past as suffering from dyscalculia. They were never diagnosed as suffering from other developmental learning disabilities such as dyslexia, dysgraphia, or attention-deficit/hyperactivity disorder (ADHD). We used an age-standardized test of arithmetic skills based on the neurocognitive model of arithmetic proposed by McCloskey, Caramazza, and Basili (1985), which was composed by Shalev, Auerbach, and Gross-Tsur (1995; for the description of the procedure see Shalev, Manor, Amir, & Gross-Tsur, 1993). We added several items to Shalev et al.'s battery to avoid a floor effect. All of these students were diagnosed as suffering from developmental dyscalculia according to the research criteria. Before running the present experiment and for comparison reasons, 41 normal university students from Ben-Gurion University of the Negev (in addition to the 17 developmental dyscalculia students) did all the tests in the battery (see also Appendix A and Table 1 in this article).

For reading assessment, we used a reading test that was composed and published by Shalev and his colleagues (Shalev et al., 1993; Shalev, Manor, Auerbach, & Gross-Tsur, 1998) and standardized for the purpose of Shalev et al.'s (2001) study. We added several items to Shalev et al.'s battery (see the current Appendix B and Table 2). Before running the present experiment and for comparison reasons, 41 normal university students from Ben-Gurion University of the Negev (in addition to the 17 developmental dyscalculia students) did all the tests in the battery. It was found that our students suffering from developmental dyscalculia did not have any reading problems, and there were no significant differences in the scores of any one of the reading tests, even in the normal range.

Scores of each individual on the Raven Progressive Matrices were converted to IQ scores, which yielded a mean IQ of 109 ($SD = 1.40$).

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

	Dyscalculia		Dyslexia		Control	
Arithmetic score	*M*	Standard score	*M*	Standard score	*M*	Standard score
Number facts						
Addition (5)	0.04	93	0.03	99	0.03	99
Subtraction (5)	0.05	89	0.02	99	0.03	101
Multiplication (5)	1.20	79	0.15	97	0.10	101
Division (5)	0.70	78	0.24	99	0.25	98
Complex arithmetic						
Addition (8)	0.71	100	0.77	98	0.75	97
Subtraction (8)	1.40	79	0.51	108	0.54	110
Multiplication (8)	2.20	87	1.10	99	1.30	98
Division (8)	4.10	78	1.70	97	1.60	99
Decimals						
Addition (4)	1.90	76	0.90	100	0.90	100
Subtraction (4)	2.30	83	1.04	97	1.00	99
Fractions						
Addition (5)	2.30	83	0.67	100	0.65	101
Subtraction (5)	2.00	87	1.10	97	1.30	95
Multiplication (5)	2.40	78	0.80	99	0.90	98
Division (5)	2.40	89	1.30	113	1.20	116

Note. Numbers in parentheses indicate the number of tasks involving each mathematical operation. The results of Part 1 of the arithmetic battery (number comprehension and production) are not presented in this table because all of these scores were intact, and there was no significant difference among the three groups.

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

	Dyscalculia			Dyslexia			Control		
Reading score	*M*	Standard score	RT	*M*	Standard score	RT	*M*	Standard score	RT
Reading comprehension									
Words (15)	0.01	102		0.08	87		0.03	99	
Text (3)	0.10	99		1.10	79		0.16	97	
Reading production									
Words (15)	0.71	115		0.99	85		0.75	114	
Words		101	568		78	658		109	501
Nonwords (15)	1.30	103		2.90	75		1.20	105	
Nonwords		94	626		78	689		115	575
Text (2)	0.02	104		0.08	85		0.03	104	
Phonological awareness (40)	0.03	109		9.80	73		0.02	111	

Note. Numbers in parentheses indicate the number of tasks involving each item. RT = reaction time.

The developmental dyslexia group. All the students in this group (13 men, among whom 11 were right handed, and 4 women, all of whom were right handed; age: $M = 24.1$, $SD = 1.8$) were diagnosed at least once in their past as suffering from dyslexia. They were never diagnosed as suffering from any other developmental learning disability such as dyscalculia, dysgraphia, or ADHD. We tested them by using the above-mentioned reading test (Shalev et al., 1993, 1998; Shalev et al., 2001). All of these students were diagnosed as suffering from developmental dyslexia according to the research criteria (see Appendix B and Table 2). In addition, they did the age-standardized test of arithmetic skills that was mentioned above (Shalev et al., 1993, 2001). It was found that they did not have any mathematical problems (see Table 1). Scores of each individual on the Raven Progressive Matrices Tests were converted to IQ scores, which yielded a mean IQ of 104 ($SD = 1.6$).

The control group. All the students in this group (13 men, among whom 10 were right handed, and 4 women, all of whom were right handed; age: $M = 22.1$ years, $SD = 3.1$) were never diagnosed as suffering from dyscalculia, dyslexia, or any other learning disability. All of them did the arithmetic, reading and Raven's Progressive Matrices Tests, which did not show any learning disability (see Tables 1 and 2). Their mean IQ score was 109 ($SD = 1.5$).

Note that in both the arithmetic and the reading battery, each participant was diagnosed separately according to Shalev and colleagues' (Shalev et al., 1993, 1998; Shalev et al., 2001) age-standardized test of arithmetic and reading skills. Because we added several items to the tests, we also compared the scores of each participant with the scores of the 41 students (presented in Tables 1 and 2). Only if a participant was found to have deficits, both according to Shalev et al.'s standardized test and according to our own norms, was he or she considered to be suffering from dyscalculia or dyslexia. We then used analysis of variance (ANOVA) to look for significant differences between the three groups.

Stimuli

A stimulus display consisted of two digits that appeared at the center of a computer screen. The center-to-center distance between the two digits was 10 mm. The participant sat 60 cm from the screen, and the stimuli subtended a horizontal visual angle of 0.7°–1.2°. Each participant performed two kinds of comparisons. In one comparison, the relevant dimension was the physical size, and in the second it was the numerical value. In every block there were 432 different stimuli. Within the set of stimuli prepared for the size and the number comparisons, each digit and each physical size appeared on both sides of the visual field an equal number of times (hence there were a total of 864 trials in each block). The 432 stimuli included 144 congruent, 144 incongruent, and 144 neutral pairs of digits. 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). A neutral stimulus was defined as a pair of digits that differed only on the relevant dimension (e.g., *5* 5 in the size task and *5 3* in the numerical task). 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).

The digits *1–9* were used, with the digit 5 excluded. 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*; and 5 = the digits *1–6*, *2–7*, *3–8*, *4–9*. Each distance included four different pairs of digits. For the physical size dimension we used eight different stimuli that created a set similar to the set of the numerical stimuli (i.e., four different pairs for each physical size distance). We chose these specific size levels because they created a semilogarithmic function similar to the pattern in which numbers are presented (Cohen Kadosh & Henik, in press; Dehaene, 1989). Recently, Melara and Algom (1996) suggested matching various dimensions in order to avoid effects of general discriminability among stimulus dimensions. Accordingly, in a separate study, all physical stimuli were matched to the numerical stimuli on participants' reaction times. Accordingly, there were eight different sizes (i.e., height of the printed Arabic numeral): 11, 12, 13, 14, 15, 16, 19, and 21 mm. These physical sizes were used to create 12 different pairs with three different size distances. The size distance of 1 (small size distance) was composed of pairs with heights 11–12, 13–14, 15–16, and 19–21 mm. The size distance of 2 (medium size distance) was composed of pairs with heights 11–13, 12–14, 15–19, and 16–21 mm. The size distance of 5 (large size distance) was composed of the following pairs: 11–15, 12–16, 13–19, and 14–21 mm.

Neutral stimuli in the physical size comparison included the same digit in two different physical sizes. In order to keep the factorial design, we created the neutral stimuli from the digits that were used for the other two conditions (congruent and incongruent). For example, because the pair *2–3* was used to produce congruent and incongruent stimuli for a numerical distance of 1 unit, neutral pairs created by using these two digits (e.g., *2 2* and *3 3*) were included in the analysis as neutral trials for numerical distance 1. Similarly, because the pair *2–4* was used to produce the congruent and incongruent conditions for a numerical distance of 2 units, neutral pairs created by using these two digits (e.g., *2 2* and *4 4*) were included in the analysis as neutral trials for numerical distance 2. Each digit from all four pairs of a given numerical distance could create two pairs of stimuli for each one of the physical distances. This was because each physical size could appear on both sides of the fixation point. Hence we had twice as many neutral trials compared with the congruent or the incongruent trials (remember that in the incongruent and congruent trials each stimulus was composed of two different digits and not of one as in the neutral trials). For example, the digit 2 could create six neutral stimuli: two in size distance of 1, two in size distance of 2, and two in size distance of 5 (e.g., for physical size distance of 1: *2–2* or *2–2*, one digit of the pair was 11 mm and the other 12 mm or vice versa; for physical size distance of 2: *2 2* or *2* 2, one digit of the pair was 11 mm and the other 13 mm or vice versa; and for size distance of 5: *2 2* or *2* 2, one digit of the pair was 11 mm and the other 15 mm or vice versa). In order to keep the number of neutral stimuli the same as the other two conditions (i.e., congruent and incongruent), we randomly chose only one of the two possible stimuli (e.g., *2–2* or *2–2*) for a given physical distance. Neutral stimuli in the numerical comparison included two different digits in the same physical sizes and were created in the same way as the neutral stimuli in the physical size comparison.

In short, each block had 27 different possible conditions: 3 (physical size distances) × 3 (numerical distances) × 3 (congruency conditions). Each condition had 32 trials: 4 (stimuli for each numerical distance) × 4 (stimuli for each physical distance) × 2 (sides) for a total of 864 trials per block.

Before every experimental block, participants were presented with 54 practice trials. This block was similar to the experimental block except that we used different distances of numbers and different physical sizes. For numerical distances of 3 units, the digits were *1–4*, *3–6*, *4–7*, and *6–9*; for numerical distances of 4 units, the digits were *1–5*, *2–6*, *3–7*, and *4–8*. For size distances of 3 units, the pair heights were 11–14, 13–15, 14–16, and 15–21 mm; for size distance of 4 units, the pair heights were 12–15, 13–16, 14–19, and 15–21 mm. Out of the 128 possible congruent trials—2 (numerical distances) × 4 (stimuli per numerical distance) × 2 (size distances) × 4 (stimuli per size distance) × 2 (opposite sides of fixation)—we randomly chose 16 trials. The same was done for the 128 possible incongruent and neutral trials.

Design

In each block, the following variables were manipulated: group (dyscalculia, dyslexia, or control), relevant dimension (physical size or numerical value), size distance (distance of 1, 2, or 5), numerical distance (1, 2, or 5), and congruity (incongruent, neutral, or congruent). Thus, we had a 3 × 2 × 3 × 3 × 3 factorial design. Group was the only between-subjects variable.

Procedure

The participant's task was to indicate, by pressing one of two optional keys, which of two digits in a given display was larger. In one block, the participant had to decide which of two digits in the given display was physically larger. In another block, the participant had to decide which of the two digits was numerically larger. The stimuli in each block were presented in a random order. Before the experiment began, participants were given a practice block. The participants were asked to respond as quickly as possible but to avoid errors. They indicated their choices by pressing one of two keys corresponding to the side of the display with the chosen digit.

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 longer than 5,000 ms). A new stimulus appeared 1,500 ms after the participant's response. Each block was 30 min in length. All the participants did both of the blocks on the same day with a 10–15-min break between them.

Results

Error rates were generally low (4% in the developmental dyscalculia group, 4.2% in the developmental dyslexia group, and 3.7% in the control group) and therefore were not analyzed. For every participant in each condition mean RT was calculated (only for correct trials). These means were subjected to a five-way ANOVA, with group as the only between-subjects factor and relevant dimension, physical size distance, numerical distance, and congruity as within-subject factors.

Five main effects were significant. Responding was fastest in the control group (mean RTs were 821 ms, 753 ms, and 526 ms, for the dyscalculia, dyslexia, and control groups, respectively), $F(2, 48) = 63.7$, $MSE = 34{,}538$, $p < .001$. Responding was faster in the physical task (669 ms) than in the numerical one (731 ms), $F(1, 48) = 5.8$, $MSE = 46{,}100$, $p < .01$. RTs varied as a function of physical distance (distance 5 units: 666 ms; distance 2 units: 710 ms; and distance 1 unit: 724 ms), $F(2, 96) = 20.32$, $MSE = 42{,}121$, $p < .001$. Similarly, RTs changed as a function of numerical distance (distance 5 units: 680 ms; distance 2 units: 693 ms; and distance 1 unit: 721 ms), $F(2, 96) = 30.53$, $MSE = 11{,}124$, $p < .001$. There was a significant congruity effect, $F(2, 96) = 45.74$, $MSE = 27{,}295$, $p < .001$, with mean RTs of 740 ms, 693 ms, and 667 ms for incongruent, neutral, and congruent pairs, respectively.

The interaction between relevant dimension and group was significant, $F(2, 48) = 4.81$, $MSE = 461{,}003$, $p = .052$, $\eta^2 = 0.614$. In the dyscalculia group, the difference between the numerical and the physical task was significantly larger than in the dyslexia group, $F(1, 48) = 8.04$, $MSE = 43{,}101$, $p < .05$, and the control group, $F(1, 48) = 4.51$, $MSE = 42{,}014$, $p < .05$.

The distance effect was indicated by the interaction of Relevant Dimension × Numerical Distance, $F(2, 96) = 9.49$, $MSE = 76{,}598$, $p < .001$, $\eta^2 = 0.819$, and is presented in Figure 2. The numerical distance was significant only in the numerical task (when numerical dimension was relevant), $F(2, 96) = 49.163$, $MSE = 7{,}508$, $p < .001$, but not in the physical task. Group did not modulate this effect.

The Group × Task × Congruity interaction was significant, $F(4, 96) = 5.64$, $MSE = 27{,}350$, $p < .05$, $\eta^2 = 0.726$, and is presented in Figure 3. In order to reveal the source of this interaction, we further analyzed the data for each task separately (Keppel, 1991). We first examined the simple interaction effects of

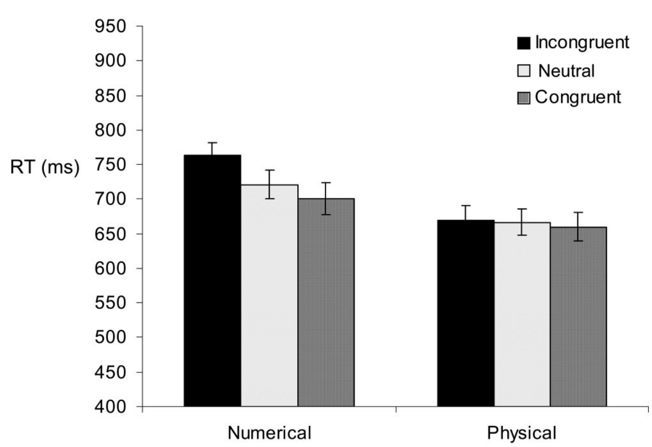

Figure 2. Reaction time (RT) as a function of task and congruity in Experiment 1.

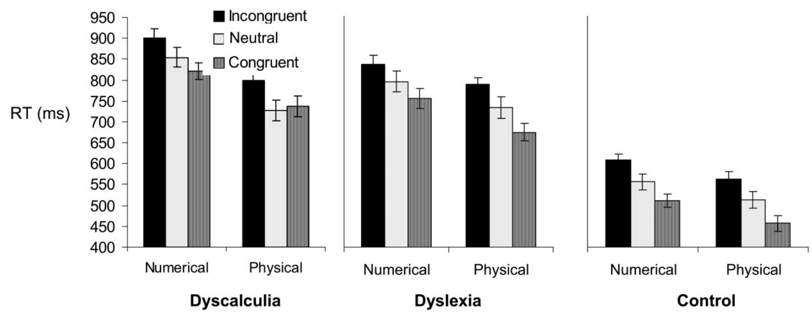

Figure 3. Reaction time (RT) as a function of group, task, and congruity in Experiment 1.

Congruity × Group for each task. The Congruity × Group interaction was not significant in the numerical task but was significant in the physical task, $F(4, 96) = 4$, $MSE = 14{,}238$, $p < .05$. Accordingly, and as can be seen in Figure 3, in the numerical task there is no difference between groups in the pattern of the congruency. In the physical task, the simple main effect of congruity was significant in all three groups of participants (dyscalculia group: $F[2, 32] = 12.2$, $MSE = 18{,}049$, $p < .001$; dyslexia group: $F[2, 32] = 22.4$, $MSE = 15{,}161$, $p < .001$; control group: $F[2, 32] = 37$, $MSE = 9{,}506$, $p < .001$). We continued by analyzing the congruity variable. Again, as can be seen in Figure 3, and according to our analysis, the congruity effect appeared in all three groups. However, in the dyscalculia group the numerical congruity effect (incongruent vs. congruent: $F[1, 16] = 9.9$, $MSE = 28{,}112$, $p < .001$) was composed only of an interference component (incongruent relative to neutral: $F[1, 16] = 26.3$, $MSE = 14{,}340$, $p < .001$). In the dyslexia group, the numerical congruity effect (incongruent vs. congruent: $F[1, 16] = 7.5$, $MSE = 8{,}884$, $p < .001$) was composed both of an interference component (incongruent relative to neutral: $F[1, 16] = 5.22$, $MSE = 22{,}480$, $p < .01$) and of a facilitation component, $F(1, 16) = 5.1$, $MSE = 23{,}541$, $p < .01$. The pattern in the control group was the same as in the dyslexia group. The numerical congruity effect, $F(1, 16) = 92.6$, $MSE = 7{,}555$, $p < .001$, was also composed both of an interference component, $F(1, 16) = 13.2$, $MSE = 9{,}862$, $p < .001$, and of a facilitation component, $F(1, 16) = 20.36$, $MSE = 11{,}098$, $p < .001$.

In addition, it should be noted that the congruity (incongruent vs. congruent) was smaller in the dyscalculia group compared with that in the dyslexia group, $F(1, 48) = 5.8$, $MSE = 2{,}485$, $p < .01$, or with that in the control group, $F(1, 48) = 5.1$, $MSE = 2{,}485$, $p < .01$. No such significant difference was found between the dyslexia and the control group.

Discussion

Let us summarize the results.

1. Group did not modulate the numerical distance effect that appeared in the numerical task (when the physical dimension was irrelevant).

2. A similar congruity effect (of the irrelevant physical sizes) was found in all three groups in the numerical task.

3. In the physical task, when numerical dimension was irrelevant, the dyscalculia group showed a significantly smaller congruity effect compared with the dyslexia and the control groups (i.e., smaller effect of the irrelevant numerical values). This effect was composed only of an interference component in the dyscalculia group and of both facilitatory and interference components in the dyslexia and control groups. These findings with the dyscalculia group replicate the findings in Rubinsten and Henik's (2005) article.

4. There was a larger difference between the slow numerical processing and the fast physical processing in students with dyscalculia than in students with dyslexia or in normal controls.

The appearance of the distance effect in all three groups indicates that all the groups, including the dyscalculia group, were perfectly able to make a large versus small classification and that they all had an intact internal number line. However, the fact that the numerical congruity effect in the physical task (when numerical values were irrelevant) found in the dyscalculia group did not resemble the effect found in the dyslexia and the control groups might indicate that the ability of the dyscalculia group to automatically associate Arabic numerals with their internal representation of magnitude is not fully automatic.

The pattern of numerical congruity in the physical size task presented by the dyscalculia group is similar to the one found with children at the end of first grade (Rubinsten et al., 2002); the numerical congruity effect is significantly smaller compared with normal university students, and it includes only the interference component.

Several reports have suggested dissociation between the interference and the facilitatory components of the Stroop effect (Henik, Singh, Beckley, & Rafal, 1993; 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, Henik, et al., 1992). As was mentioned earlier, Posner (1978) suggested that facilitation is an indicator of automaticity, whereas interference might reflect attentional processing. The idea that people with developmental dyscalculia might have deficits in automatic processing related to numbers is not new. Koontz and Berch (1996), for example, found that for children with arithmetic learning disabilities, naming three dots (i.e., saying the word *three*) took longer than naming two dots. This result suggests that the children with developmental dyscalculia were counting the dots. Thus, the *subitizing* (i.e., automatically determining the magnitude of small sets of numbers) range of children with developmental dyscalculia might have been smaller than that of the children in the control group. This might indicate that children with developmental dyscalculia have damage in automatic processing related to basic numerical processing.

It is known that an arbitrary keypress is much more difficult for people with learning disabilities (e.g., Rubinsten & Henik, 2005). Koontz and Berch (1996) found that children with arithmetical learning disabilities are slower in naming letters compared with those in a control group, and S. E. Shaywitz (2003) claimed in her review article that people with dyslexia are slower in reading. Moreover, the dyscalculia group in the current study showed a larger difference in general RT between the slow numerical processing and the relatively fast physical processing than the other two groups did. Hence, it seems that in dyscalculia, the ability to confront a physical dimension is very different from the ability to confront a numerical dimension. In contrast, in normal students or even in students with dyslexia, numerical values are processed much more like physical sizes. Considering the fact that physical sizes are automatically processed from infancy, we argue that in dyscalculia, numerical values are not being processed fast enough or in an automatic and efficient way. Note that the current study was carried out on adults and hence, it is necessary that a similar study is conducted with children in order to generalize our results to populations of children suffering from dyscalculia.

It should be noted that Landerl et al. (2004) tested groups of children suffering from developmental dyscalculia, dyslexia, both difficulties, and those with neither on a range of numerical tasks, including physical and numerical Stroop tasks. In contrast with our findings, in the Stroop task for the physical condition no effects of congruency were found in any of the groups. This is a surprising finding because many articles have reported a size congruity effect in the normal population (e.g., Henik & Tzelgov, 1982; Rubinsten et al., 2002; Tzelgov, Meyer, & Henik, 1992). Hence, it would be expected that the effect would appear at least in the control group.

Experiment 2

Several reports have suggested that when two written letters with the same phoneme are manipulated (e.g., when children learn in each trial to associate two different graphemes with their phonemes), reaction times are longer and there are more errors compared with when two letters with different phonemes are manipulated (e.g., Lange, 2002; Mauer & Kamhi, 1996; Ziegler & Jacobs, 1995; Ziegler, Van Orden, & Jacobs, 1997). The current study was designed to examine whether phoneme similarity has a unique effect on performance of students suffering from learning disabilities. More specifically, we used Navon figures (Navon, 1977) in order to determine whether phoneme similarity modulates the ability of these students to ignore irrelevant letters. Single Hebrew letters (i.e., global) were created by local letters that sound the same (i.e., a same sound trial; see Figure 1) or by letters that sound different (i.e., a different sound trial; see Figure 1). The participant's task was to name either the large letter (global) and to ignore the small letters (local) or, in a different block, to name the small letters and to ignore the large letter.

Note that in contrast with the incongruent and congruent trials in the numerical Stroop task, in the present task it was expected that RT to different sound trials would be shorter than RT to same sound trials. We refer to this effect as the *phonological congruity effect*.

As in the first experiment, we also wanted to look at the interference and facilitatory components by using neutral stimuli in which the irrelevant dimension did not trigger any irrelevant processing (i.e., it did not result in any facilitation or interference). Accordingly, the neutral stimuli were large Hebrew letters built of meaningless Gibson figures, which are arbitrary figures created out of digits and letters (e.g., ▷, see Figure 4 for examples; Gibson, 1966) or large Gibson figures built of small Hebrew letters.

Method

Participants

We used the same participants as in the previous experiment.

Stimuli

A stimulus display consisted of one large symbol (i.e., Hebrew letter or Gibson figure, e.g., ▷) that was built of a grouping of small symbols (i.e., Hebrew letter or Gibson figure). The stimulus appeared at the center of a computer screen after the appearance of a temporary fixation point. The participant sat 60 cm from the screen. Each participant performed two kinds of comparisons. In one, the relevant dimension was the large letter (i.e., global task), and, in the other, the relevant dimension was the small letters (i.e., the local task). In every block there were 24 different stimuli. Within the set of stimuli prepared for each task, each stimulus was randomly presented three times (hence there was a total of 72 trials in each block). The 24 stimuli included 8 same sound, 8 different sound, and 8 neutral pairs of symbols. A *same sound* stimulus was defined as a stimulus in which both the large letter (global) and the small letters (local; e.g., the Hebrew letter ת that sounds like /t/ was written with small letters of ק that sound like /k/) had the same phonemes (e.g., the Hebrew letter ת that sounds like /t/ was written with small letters of ט that sound also like /t/; see Figure 1); a *different sound* stimulus was defined as a stimulus in which the large letter had a different phoneme from the small letters (local; e.g., the Hebrew letter ת that sounds like /t/ was written with small letters of ק that sound like /k/). A *neutral stimulus* was defined as a letter that appeared only on the relevant dimension (local or global), and on the irrelevant dimension a Gibson figure appeared (e.g., the Hebrew letter ת that sounds like /t/ was written with small Gibson figures such as ▷, or in the global task a large Gibson figure was written with small Hebrew letters such as ת).

We used four pairs of letters that have the same phoneme: א and ע both sound like /a/, ת and ט both sound like /t/, ב and ו both sound like /v/, and כ and ק both sound like /k/. Hence, each letter had only one same sound option in each one of the tasks (e.g., in the global task the Hebrew letter ת that sounds like /t/ could appear only once as a same sound trial when it was written with small letters of ט that sound also like /t/. In the local task, it also could appear only once as a same sound trial when many small ת letters created a large ט letter). Notice that in each one of the tasks each such stimulus was presented four times. However, each letter in each one of the tasks had six different sound options (because there were six remaining letters out of the total eight that did not have the same sound). In such a case we might have had six times as many different sound trials compared with the same sound trials. In order to keep the factorial design, the computer randomly chose only one of the six optional letters. In this way the comparison between the same sound and the different sound was made by using the same letters (across all the participants). For the neutral trial, we used eight optional Gibson figures (see Figure 4) for each one of the eight Hebrew letters, from which the computer randomly chose only one of the Gibson figures for simultaneous presentation (this was done separately for each one of the participants).

In short, each block of the two tasks (global or local) had three different possible conditions (i.e., same sound, different sound, and neutral). Each condition had 24 trials: 8 (different stimuli) $\times$ 3 (presentations) for a total of 72 trials per block.

Twenty-four practice trials preceded each one of the two experimental blocks. The practice block was similar to the experimental block except that we used different pairs of letters (only two pairs of letters). Because there are no other Hebrew letters that have the same phoneme, we used letters that are very close in their sounds (i.e., the letter צ that sounds as /ts/ with the letter ז that sounds like /z/, and the letter ש that in some cases sounds like /sh/ with the letter ס that sounds like /s/).

Design

The following variables were manipulated: group (dyscalculia, dyslexia, control), task (global or local), and similarity (same sound, different sound or neutral). Thus, we had a $3 \times 2 \times 3$ factorial design. Group was the only between-subjects variable.

Procedure

The participant's task was to name either the global or the local letter (in separate blocks). Each participant took part in two sessions on the same day. Each session was composed of one block and one task. The stimuli in each block were presented in a random order. Before the experiment began, participants were given a practice block. They were asked to respond as quickly as possible but to avoid errors.

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

Results

Error rates were generally low (2% in the developmental dyscalculia group, 2.2% in the developmental dyslexia group, and 1.7% in the control group) and therefore were not analyzed. For every participant in each condition mean RT was calculated (only for correct trials). These means were subjected to a three-way ANOVA with group as the only between-subjects factor and task and congruity as within-subject factors.

Two main effects were significant. Responding was the fastest in the control group (mean RTs: 556 ms, 565 ms, and 506 ms for the dyscalculia, the dyslexia, and the control group, respectively), $F(2, 48) = 5$, $MSE = 74{,}011$, $p < .05$. There was also a significant phonological congruity effect, $F(2, 96) = 4.1$, $MSE = 50{,}331$, $p < .01$, with mean RTs of 569 ms, 541 ms, and 502 ms for same sound, neutral, and different sound pairs, respectively. There was no significant difference in RT between the two tasks.

The Group $\times$ Congruity interaction was significant, $F(4, 96) = 4.7$, $MSE = 50{,}331$, $p < .001$, $\eta^2 = 0.591$, and is presented in Figure 5. In order to reveal the source of this interaction, we examined the phonological congruity effect (same sound vs. different sound) in each group separately. As can be seen in Figure 5, and according to our analysis, in the dyslexia group the phonological congruity effect, $F(1, 16) = 4.3$, $MSE = 42{,}987$, $p < .05$, was composed of neither facilitation nor interference (i.e., facilitation and interference components were not significant). Most important, this phonological congruity effect was smaller in the dyslexia group compared with that in the dyscalculia group, $F(1, 48) = 5.3$, $MSE = 47{,}231$, $p < .05$, and compared with the control group, $F(1, 48) = 5.7$, $MSE = 47{,}441$, $p < .05$. In the dyscalculia group and the control group, the phonological congruity effect (dyscalculia group: $F[1, 16] = 5.54$, $MSE = 52{,}431$, $p < .01$; control group: $F[1, 16] = 6.43$, $MSE = 40{,}321$, $p < .001$) was composed of both an interference component (i.e., same sound relative to neutral; dyscalculia group: $F[1, 16] = 5.03$, $MSE = 48{,}562$, $p < .001$; control group: $F[1, 16] = 7.44$, $MSE = 25{,}465$, $p < .001$) and of a facilitation component (i.e., different sound relative to neutral; dyscalculia group: $F[1, 16] = 6.1$, $MSE = 85{,}832$, $p < .01$; control group: $F[1, 16] = 5.79$, $MSE = 51{,}876$, $p < .01$).


Figure 4. Gibson figures that were used in Experiment 2.

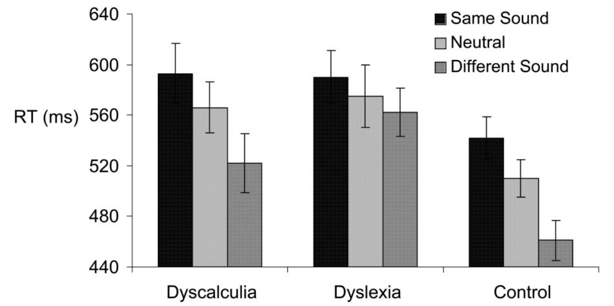

Figure 5. Reaction time (RT) as a function of group and congruity in Experiment 2.

Discussion

Irrespective of task, all three groups were able to name single letters. However, whereas phoneme similarity modulated performance of the control and the dyscalculia groups, it had a very small effect on performance of the dyslexia group. The phonological congruity effect in this group was smaller than in the other two groups and showed no significant interference or facilitation. In the control and dyscalculia groups, the irrelevant letter could not be ignored and was processed automatically. It seems that in the control and dyscalculia groups each letter is strongly and automatically connected with its own sound.

The results of the control group fit other findings that indicate that multiple grapheme–phoneme associations are available and activated during phonological transcoding. For example, Lange (2002) found that letter detection is affected by phonological similarity between a target nonword and the original word used to produce the target.

Our experiment shows that people suffering from developmental phonological dyslexia have problems in automatically associating graphemes to phonemes. Mauer and Kamhi (1996) reached a similar conclusion. They taught children suffering from reading disabilities and matched controls (aged 5.2–9.3 years) to associate graphemes to phonemes. They found that the control groups learned to associate graphemes with their phonemes in significantly fewer trials than the children suffering from reading disabilities. Moreover, phonological similarity between the to-be-learned letters produced much more difficulty in the children with reading disabilities than in the control children.

Several researchers have suggested that the ability to simultaneously attend to letters and their sounds (i.e., *decoding*) plays a fundamental role in establishing rapid word or letter recognition ability (Share, 1995; Share & Stanovich, 1995). Share and Stanovich (1995) have argued that practicing decoding skills is an efficient way to strengthen word reading ability and to make it automatic. This may be achieved, for example, through self-teaching, which enables the learner to independently acquire an autonomous orthographic lexicon (for a review see Share, 1995). Decoding letters into sounds provides a child with the means to both generate plausible pronunciations for unfamiliar visual words and to generate error signals that allow successive approximations to correct phonological patterns.

It is possible that the control and dyscalculia groups had an intact practice in associating letters with their phonemes. In contrast, people suffering from dyslexia, because of their phonological impairment, did not have such an intact practice. This fits with McCandliss and Noble's (2003) suggestion that there is a developmental sequence in acquiring reading skills—from phonological processing to grapheme–phoneme decoding. Functional anomalies in the left perisylvian region, which is related to phonological processing, may lead to childhood deficits in phonological processing that are crucial for grapheme–phoneme decoding. In normally developing children, successful application of decoding skills involves the visual word form. The visual word form is subserved by the fusiform gyrus, whose activation requires intact phonological skills subserved by perisylvian regions. Note, however, that Castles and Coltheart (2003) suggested that the ability to perceive and manipulate sounds of spoken language does not assist literacy acquisition, nor does the acquisition of reading and spelling ability affect phonological awareness. Rather, the association between the two (phonological awareness and decoding) arises because both are indices of orthographic skill. If this is the case, then it is not the phonological impairment that leads to problems in associating phonemes with letters, but rather people with dyslexia have specific problems both in phonological awareness and in automatically associating letters with phonemes. Our results cannot determine which suggestion (Castles & Coltheart, 2003 vs. McCandliss & Noble, 2003) is viable. They suggest that the strength of association between written letters and phonemes in developmental dyslexia is weak and not automatic.

General Discussion

The most interesting finding of this work is the dissociation of functions between people with dyslexia and dyscalculia: The dyscalculia group has problems in automatically associating Arabic numerals with their internal representation of magnitudes but has no problems in automatically associating letters with their phonemes, whereas the dyslexia group shows the opposite pattern.

Steeves (1983) showed that 10% of the children suffering from dyslexia were considered to be very good mathematicians, 30% did not have any problems in math, and 25% had math problems that were due to reading difficulties (i.e., problems in reading the questions). Since the time of that study it has become an acceptable fact that math disorders can appear with or without reading disabilities. Our results support the suggestion that the development of symbolic competence in different symbolic domains (i.e., digits and letters), and more specifically, the ability to associate those symbols with their internal representations, is domain specific. These behavioral findings fit with suggestions that separate brain areas are associated with grapheme–phoneme and digit-magnitude correspondences (e.g., Dehaene & Cohen, 1995; Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Fias et al., 2003; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Price, Moore, Humphreys, & Wise, 1997; Rumsey et al., 1997).

As was previously mentioned, the assessment of learning disabilities and methods for improving such disabilities require careful analysis of component skills. Educators are in need of empirically based screening and intervention tools for learning disabilities, and, hence, it is important to first clearly define what we seek to identify and remediate. Therefore, studying basic cognitive processes, such as the ability to automatically associate symbols with their mental representations, is necessary for developing efficient techniques for improving learning disabilities (Ansari & Coch, 2006; Rayner et al., 2001).

For example, our work might point to the fact that before starting to learn mathematics or reading, children first need to be able to automatically and very efficiently associate symbols with their mental representations. More specifically, people suffering from dyslexia need to learn how to automatically associate letters with phonemes, and people suffering from dyscalculia need to learn how to automatically associate digits with quantities. Can this be done? Hasher and Zacks (1979) and Logan (1988) argued that the degree of automaticity is reflected in the speed of processing and correlates with proficiency; as skill develops processing becomes faster, which means that it is more automatic. Accordingly, practice with associations between phonemes and letters and between digits and magnitudes might improve reading and mathematical abilities of people suffering from dyslexia or from dyscalculia. Tzelgov and his colleagues (Tzelgov, Yehene, Kotler, & Alon, 2000), for example, taught university students to associate Gibson figures (i.e., meaningless figures that were created from letters and digits) with magnitudes. They presented participants pairs of Gibson figures having adjacent values (i.e., Gibson figures that represent 1 and 2 or 2 and 3, etc.). The assigned values of the various Gibson figures were not presented to the participants, so that at the beginning of the study phase they were just guessing. After six study sessions participants showed a distance effect and size congruity effect with the Gibson figures. These effects appeared with pairs of figures never experienced before by the participants (recall that they experienced only Gibson figures indicating adjacent magnitudes like 3–4 but not those indicating magnitudes such as 3–5 or 3–7). Namely, the irrelevant size and/or quantity values of the Gibson figures interfered with comparisons of their relevant physical sizes. This indicates that the association between the Gibson figures and the magnitudes were automatized (see also Ashkenazi, Rubinsten, Goldfarb, & Henik, 2006). We are now in the process of studying whether such effects with Gibson figures appear with children and adults suffering from learning disabilities.

Several articles point to two cortical areas that show dysfunction in developmental dyslexia. The first region, the left perisylvian area, typically involving the superior temporal gyrus, is essential for phonological processing (e.g., Price et al., 1997; Rumsey et al., 1997). The second region, a portion of the left occipito-temporal extrastriate visual system, typically centered on or near the middle portion of the fusiform gyrus, has been associated with automatic processing of visual word form perception in skilled adult readers. That is, skilled readers develop a form of visual expertise that allows them to automatically combine the letters of a word into an integrated visual percept. This region is often referred to as the *visual word form area* (VWFA; for a review see Rayner & Pollatsek, 1995).

As has been suggested by several researchers, and mentioned earlier in this article, the ability to simultaneously attend to letters and their sounds (i.e., decoding) plays a fundamental role in establishing rapid word or letter recognition ability (Share, 1995; Share & Stanovich, 1995). B. A. Shaywitz et al. (2002) have provided support for the developmental connection between the ability to associate graphemes with phonemes and the development of the VWFA. In their study, involving over 140 children aged 7–18 years old, who either suffered from dyslexia or were nonimpaired, decoding ability was positively correlated with the degree of VWFA activation in response to pseudowords. This correlation suggests that efficient associations between graphemes and phonemes involve the left fusiform gyrus, which becomes tuned to word structure via experience.

What about representations of numbers and magnitudes? The parietal lobes are involved in the representation and manipulation of magnitudes (Dehaene & Cohen, 1995). For example, by using fMRI Fias et al. (2003) found that a certain area in the left intraparietal sulcus was specifically responsive to abstract magnitudes, regardless of stimulus type (i.e., angles, lines, and two-digit numbers). Fias et al. showed that a region slightly anterior to the left intraparietal sulcus is particularly involved in Arabic number comparison. The authors suggested that this region might be responsible for the decoding (i.e., digit-magnitude association) of two-digit numbers. Cohen, Dehaene, Chochon, Lehericy, and Naccache (2000) reported the case of a patient who suffered from aphasia, deep dyslexia, and acalculia following a lesion to her left perisylvian area. She showed a severe impairment in all tasks involving numbers in a verbal format. In contrast, her ability to manipulate Arabic numerals and quantities was well preserved. That is, numerical processing was largely preserved as long as no decoding of numbers in a verbal format was required. When she was presented with Arabic numerals, she could access and manipulate the associated quantities. It should be noted that she had a brain lesion in the classical language areas but not in the left inferior parietal lobule that was found by using fMRI to be active during calculation tasks. Although the scope of Cohen et al.'s (2000) article prevented them from exploring the brain area that is related specifically to decoding Arabic numerals, their results together with those of Fias et al. suggest that part of the left parietal lobe is involved in the association of Arabic numerals and their internal representation of magnitudes. Although further research mainly in the field of number processing is needed, it could still be argued that different brain areas are associated with grapheme–phoneme and with digit-magnitude correspondences. The association of graphemes and phonemes involves a portion of the left fusiform gyrus (i.e., the VWFA), and associating Arabic numerals with their internal representation of magnitude might involve a part of the left parietal lobe. The reliance of decoding in separate brain areas might lead to the dissociation in functions reported in this work.

References

Algom, D., Dekel, A., & Pansky, A. (1996). The perception of number from the separability of the stimulus: The Stroop effect revisited. *Memory & Cognition, 24,* 557–572.

American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: American Psychiatric Association.

Ansari, D., & Coch, D. (2006). Bridges over troubled waters: Education and cognitive neuroscience. *Trends in Cognitive Science, 10,* 146–151.

Ansari, D., & Karmiloff-Smith, A. (2002). Atypical trajectories of number development: A neuroconstructivist perspective. *Trends in Cognitive Sciences, 6,* 511–516.

Ardila, A., & Rosselli, M. (2003). Acalculia and dyscalculia. *Neuropsychology Review, 12,* 179–231.

Ashkenazi, S., Rubinsten, O., Goldfarb, L., & Henik, A. (2006). *Automatic activation of magnitude (on year) after magnitude association training.* Manuscript in preparation.

Bailey, C. E., Manis, F. R., Pedersen, W. C., & Seidenberg, M. S. (2004). Variation among developmental dyslexics: Evidence from a printed-word-learning task. *Journal of Experimental Child Psychology, 87,* 125–154.

Besner, D., & Coltheart, M. (1979). Ideographic and alphabetic processing in skilled reading of English. *Neuropsychologia, 17,* 467–472.

Bishop, D. V. M., & Adams, C. (1990). A prospective study of the relationship between specific language impairment, phonological disorders, and reading retardation. *Journal of Child Psychology and Psychiatry and Applied Disciplines, 31,* 1027–1050.

Bradley, L., & Bryant, P. E. (1983, February 3). Categorizing sounds and learning to read: A causal connection. *Nature, 301,* 419–421.

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

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

Castles, A., & Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition, 47,* 149–180.

Castles, A., & Coltheart, M. (2003). Is there a causal link from phonological awareness to success in learning to read? *Cognition, 91,* 77–111.

Castles, A., Datta, H., Gayan, J., & Olson, R. K. (1999). Varieties of developmental reading disorder: Genetic and environmental influence. *Journal of Experimental Child Psychology, 72,* 73–94.

Cohen, L., Dehaene, S., Chochon, F., Lehericy, S., & Naccache, L. (2000). Language and calculation within the parietal lobe: A combined cognitive, anatomical and fMRI study. *Neuropsychologia, 38,* 1426–1440.

Cohen Kadosh, R., & Henik, A. (in press). *A common representation for semantic and physical properties: A cognitive-anatomical approach. Experimental Psychology*.

Cohen Kadosh, R., Henik, A., Rubinsten, O., Mohr, H., Dori, H., Van de Ven, V., et al. (2005). Are numbers special? The comparison systems of the human brain investigated by fMRI. *Neuropsychologia, 43,* 1238–1248.

Dehaene, S. (1989). The psychophysics of numerical comparison: A reexamination of apparently incompatible data. *Perception & Psychophysics, 45,* 557–566.

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

Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition, 1,* 83–120.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 626–641.

DeLoache, J. S. (2004). Becoming symbol-minded. *Trends in Cognitive Sciences, 8,* 66–70.

Duncan, E. M., & McFarland, C. E. (1980). Isolating the effect of symbolic distance and semantic congruity in comparative judgments: An additive factors analysis. *Memory & Cognition, 2,* 95–110.

Eger, E., Sterzer, P., Russ, M. O., Giraud, A. L., & Kleinschmidt, A. (2003). A supramodal number representation in human intraparietal cortex. *Neuron, 37,* 719–725.

Facoetti, A., Lorusso, M. L., Paganoni, P., Cattaneo, C., Galli, R., Umilta, C., et al. (2003). Auditory and visual automatic attention deficits in developmental dyslexia. *Cognitive Brain Research, 16,* 185–191.

Fias, W., Lammertyn, J., & Reynvoet, B. (2003). Parietal representation of symbolic and nonsymboic magnitude. *Journal of Cognitive Neuroscience, 15,* 47–56.

Gallistel, C. R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition, 44,* 43–74.

Geary, D. C. (2004). Mathematical and learning disabilities. *Journal of Learning Disabilities, 37,* 4–15.

Geary, D. C., Hamson, C. O., & Hoard, M. K. (2000). Numerical and arithmetical cognition: A longitudinal study of process and concept deficits in children with learning disability. *Journal of Experimental Child Psychology, 77,* 236–263.

Gelfand, J. R., & Bookheimer, S. Y. (2003). Dissociating neural mechanisms of temporal sequencing and processing phonemes. *Neuron, 38,* 831–842.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin.

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

Goswami, U. (2003). Why theories about developmental dyslexia require developmental designs. *Trends in Cognitive Sciences, 7,* 534–540.

Hasher, L., & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General, 108,* 356–388.

Henik, A., Singh, J., Beckley, D. J., & Rafal, R. D. (1993). Disinhibition of mental word reading in Parkinson's disease. *Cortex, 29,* 589–599.

Henik, A., & Tzelgov, J. (1982). Is three greater than five: The relation between physical and semantic size in comparison tasks. *Memory & Cognition, 10,* 389–395.

Hinshelwood, J. (1917). *Congenital word blindness.* London: H. K. Lewis.

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

Jenner, A. R., Rosen, G. D., & Galaburda, A. M. (1999). Neuronal asymmetries in primary visual cortex of dyslexic and nondyslexic brains. *Annals of Neurology, 46,* 189–196.

Kaufmann, L., Lochy, A., Drexler, A., & Semenza, C. (2004). Deficient arithmetic fact retrieval: Storage or access problem? A case study. *Neuropsychologia, 42,* 482–496.

Keppel, G. (1991). *Design and analysis: A researcher's handbook* (3rd ed.). Upper Saddle River, NJ: Prentice Hall.

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

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

Lange, M. (2002). Activation of multiple phoneme associates of graphemes in visual word recognition. *Brain and Language, 81,* 610–620.

Lindsay, D. S., & Jacoby, L. L. (1994). Stroop process dissociation: The relationship between facilitation and interference. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 219–234.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review, 95,* 492–527.

Mauer, D. M., & Kamhi, A. G. (1996). Factors that influence phoneme-grapheme correspondence learning. *Journal of Learning Disabilities, 29,* 259–270.

McCandliss, B. D., & Noble, K. G. (2003). The development of reading impairment: A cognitive neuroscience model. *Mental Retardation and Developmental Disabilities Research Reviews, 9,* 196–205.

McCloskey, M., Caramazza, A., & Basili, A. (1985). Cognitive mechanisms in number processing and calculation: Evidence from dyscalculia. *Brain and Cognition, 4,* 171–196.

Melara, R. D., & Algom, D. (1996, November 3). *Stroop and selective attention: Putting it all in context.* Paper presented at the 37th Annual Meeting of the Psychonomic Society, Chicago, IL.

Molko, N., Cachia, A., Rivière, 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.

Morgan, J. (1896). A case of congenital word blindness. *British Medical Journal, 2*, 1378.

Moyer, R. S., & Landauer, T. K. (1967, September 30). Time required for judgment of numerical inequality. *Nature, 215,* 1519–1520.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology, 9,* 353–383.

Nicholson, R. I., & Fawcett, A. J. (1990). Automaticity: A new framework for dyslexia research. *Cognition, 35,* 159–182.

Orton, S. T. (1937). *Reading, writing and speech problems in children.* New York: Norton.

Pansky, A., & Algom, D. (1999). Stroop and Garner effects in comparative judgments of numerals: The role of attention. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 39–58.

Pinel, P., Piazza, M., Le Bihan, D., & Dehaene, S. (2004). Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. *Neuron, 41,* 983–993.

Poldrack, R. A., Temple, E., Protopapas, A., Nagarajan, S., Tallal, P., Merzenich, M., et al. (2001). Relations between the neural bases of dynamic auditory processing and phonological processing: Evidence from fMRI. *Journal of Cognitive Neuroscience, 13,* 687–697.

Posner, M. I. (1978). *Chronometric explorations of mind.* Hillsdale, NJ: Erlbaum.

Price, C. J., Moore, C. J., Humphreys, G. W., & Wise, R. J. S. (1997). Segregating semantic from phonological processes during reading. *Journal of Cognitive Neuroscience, 9,* 727–733.

Raberger, T. W. H. (2003). On the automaticity/cerebellar deficit hypothesis of dyslexia: Balancing and continuous rapid naming in dyslexic and ADHD children. *Neuropsychologia, 41,* 1493–1497.

Ramus, F. (2001, July 26). Talk of two theories. *Nature, 412,* 393–395.

Ramus, F. (2003). Developmental dyslexia: Specific phonological deficit or general sensorimotor dysfunction? *Current Opinion in Neurobiology, 13,* 212–218.

Rayner, K., Foorman, B. R., Perfetti, C. H., Pesetsky, D., & Seidenberg, M. S. (2001). How psychological science informs the teaching of reading. *Psychological Science in the Public Interest, 2,* 31–74.

Rayner, K., & Pollatsek, A. T. (1995). *The psychology of reading*: Mahwah, NJ: Erlbaum.

Robertson, L. C., Lamb, A. R., & Zaidel, E. (1993). Interhemispheric relations in processing hierarchical patterns: Evidence from normal and commissurotomized subjects. *Neuropsychology, 7,* 325–342.

Rubinsten, O., & Henik, A. (2005). Automatic activation of internal magnitude: A study of developmental dyscalculia. *Neuropsychology, 19,* 641–648.

Rubinsten, O., Henik, A., Berger, A., & Shahar-Shalev, S. (2002). The development of internal representations of magnitude and their association with Arabic numerals. *Journal of Experimental Child Psychology, 81,* 74–92.

Rumsey, J. M., Horwitz, B., Donohue, B. C., Nace, K., Maisog, J. M., & Andreason, P. (1997). Phonological and orthographic components of word recognition: A PET-rCBF study. *Brain, 120,* 739–759.

Schwartz, W., & Ischebeck, A. (2003). On the relative speed account of number-size interference in comparative judgments of numerals. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 507–522.

Schwarz, W., & Heinze, H.-J. (1998). On the interaction of numerical and size information in digit comparison: A behavioral and event-related potential study. *Neuropsychologia, 36,* 1167–1179.

Shalev, R. S., Auerbach, J., & Gross-Tsur, V. (1995). Developmental dyscalculia behavioral and attentional aspects: A research note. *Journal of Child Psychology and Psychiatry and Applied Disciplines, 36,* 1261–1268.

Shalev, R. S., Manor, O., Amir, N., & Gross-Tsur, V. (1993). Acquisition of arithmetic in normal children: Assessment by a cognitive model of dyscalculia. *Developmental Medicine and Child Neurology, 35,* 593–601.

Shalev, R. S., Manor, O., Auerbach, J., & Gross-Tsur, V. (1998). Developmental dyscalculia: What counts. Prospective 3-year follow-up. *Journal of Pediatrics, 133,* 358–362.

Shalev, R. S., Manor, O., Kerem, B., Ayali, M., Badichi, N., Friedlander, Y., et al. (2001). Developmental dyscalculia is a familial learning disability. *Journal of Learning Disabilities, 34,* 59–65.

Share, D. L. (1995). Phonological recoding and self-teaching: Sine qua non of reading acquisition. *Cognition, 55,* 151–218.

Share, D. L., & Stanovich, K. E. (1995). Cognitive processes in early reading development: Accommodating individual differences into a model of acquisition. *Issues in Education, 1,* 1–57.

Shaywitz, B. A., Shaywitz, S. E., Puch, K. R., Mencl, W. E., Fulbright, R. K., Skudlarksi, P., et al. (2002). Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry, 52,* 101–110.

Shaywitz, S. E. (2003). Dyslexia. *The New England Journal of Medicine, 338,* 307–312.

Snowling, M. J. (1991). Developmental reading disorder. *Journal of Child Psychology and Psychiatry, 32,* 49–77.

Stanovich, K. (1988). Explaining the differences between the dyslexic and the garden-variety poor reader: The phonological core, variable-difference model. *Journal of Learning Disabilities, 21,* 590–612.

Stanovich, K. E., Siegel, L. S., & Gottardo, A. (1997). Converging evidence for phonological and surface subtypes of reading disability. *Journal of Educational Psychology, 89,* 114–127.

Steeves, K. J. (1983). Memory as a factor in the computational efficiency of dyslexic children with high abstract reasoning ability. *Annals of Dyslexia, 33,* 141–152.

Stein, J. (2001). The sensory basis of reading problems. *Developmental Neuropsychology, 20,* 509–534.

Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends in Neuroscience, 20,* 147–152.

Tzelgov, J., Henik, A., & Berger, J. (1992). Controlling Stroop effects by manipulating expectations for color words. *Memory & Cognition, 20,* 727–735.

Tzelgov, J., Henik, A., Sneg, R., & Baruch, O. (1996). Unintentional word reading via the phonological route: The Stroop effect in cross-script homophones. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 336–349.

Tzelgov, J., Meyer, J., & Henik, A. (1992). Automatic and intentional processing of numerical information. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 166–179.

Tzelgov, J., Yehene, V., Kotler, L., & Alon, A. (2000). Automatic comparisons of artificial digits never compared: Learning linear ordering relations. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 1–18.

Vaid, J., & Corina, D. (1989). Visual field asymmetries in numerical size comparisons of digits, words and signs. *Brain and Language, 36,* 117–126.

Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101,* 192–212.

Wolff, P. H. (2002). Timing precision and rhythm in developmental dyslexia. *Reading and Writing: An Interdisciplinary Journal, 15,* 179–206.

Wolff, P. H., Michel, G. F., & Ovrut, G. F. (1990). The timing of syllable repetitions in developmental dyslexia. *Journal of Speech and Hearing Research, 33,* 281–289.

Wolff, P. H., Michel, G. F., Ovrut, G. F., & Drake, C. (1990). Rate and timing of motor coordination in developmental dyslexia. *Developmental Psychology, 26,* 349–359.

Yap, R. L., & Van Der Leij, A. (1994). Testing the automatisation deficit hypothesis of dyslexia via a dual task paradigm. *Journal of Learning Disabilities, 27,* 660–665.

Ziegler, J. C., & Jacobs, A. M. (1995). Phonological information provides early sources of constraint in the processing of letter strings. *Journal of Memory and Language, 34,* 567–593.

Ziegler, J. C., Van Orden, G. C., & Jacobs, A. M. (1997). Phonology can help or hurt the perception of print. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 845–860.

Appendix A

Arithmetic Battery

Part 1: Number Comprehension and Production

Tests Devised Primarily for Number Comprehension

A: Matching written Arabic numerals to quantities. In a multiple-choice task, participants matched the appropriate quantity of drawn stimuli (dots, dashes, and triangles) to a single written Arabic numeral. There were five such tasks, and the numbers ranged from 3 to 12.

B: Comprehension of quantities. Two groups of nonnumerical stimuli of different shapes (dots, dashes, etc.) were drawn on five cards. The number of stimuli on each card ranged from two to seven. Participants were asked to indicate whether a particular group had more, fewer, or the same number of stimuli.

C: Comprehension of numerical values. Participants were presented with five pairs of written Arabic numerals, and for each pair they had to identify which number was larger or which was smaller.

D: Serial order. Participants were presented with a sequence of written numbers, which they had to put in order from largest to smallest.

Tasks Designed for Number Production

A: Counting. Participants were asked to count aloud numbers of stimuli (dots, dashes, etc.) appearing in rows or groups. The number of stimuli ranged from 5 to 14. There were five such tasks.

B: Production (writing) of numbers. Participants were instructed to copy and read five numbers, between one and four digits long and to write five additional one- to four-digit numbers that were dictated to them.

Part 2: Calculation—Number Facts

Participants were required to solve 20 simple addition, subtraction, multiplication, and division exercises.

Part 3: Calculation—Complex Exercises

Participants had to compute complex written arithmetic problems (addition, subtraction, multiplication, and division). The first 16 exercises were addition and subtraction, and the remaining 16 were multiplication and division.

Part 4: Decimals and Fractions

There were 4 complex addition and 4 complex subtraction exercises requiring knowledge of decimals. There were 20 simple exercises with fractions: 5 addition, 5 subtraction, 5 multiplication, and 5 division.

Appendix B

Reading Battery

Part 1: Reading Comprehension and Production

A: Vocabulary. Fifteen words were taken from the Wechsler Adult Intelligence Scale, which participants had to explain.

B: Text. In a multiple-choice task (a total of 14 questions), participants read 3 different texts and answered a total of 14 multiple-choice questions.

C: Reading words. Fifteen words appeared on the computer screen and measures of both reaction times and accuracy were taken.

D: Reading nonwords. Fifteen nonwords appeared on the computer screen and measures of both reaction times and accuracy were taken.

E: Reading texts. Participants had to read two different texts.

Part 2: Phonological Awareness

A: Associating letters with their sounds. Participants had to choose two words that start with the same sound out of four different words. There were 10 such tasks.

B: Omission. Participants had to omit a sound in 20 different words and indicate how the new “word” sounded.

C: Rhymes. Participants had to choose out of four different words, the one that rhymed with a particular word. There were 10 such tasks.

Received July 21, 2005
Revision received May 30, 2006
Accepted May 31, 2006 ■