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The Association of Rapid Temporal Perception With Orthographic and Phonological Processing in Children and Adults With Reading Impairment

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Adults and children with reading impairment ($N = 67$) were administered a rapid auditory task, a rapid visual task, and a battery of orthographic and phonological tasks. Our results support a differential development model of reading disability that argues that deficits in rapid auditory ability in children are primarily associated with problems in phonological processing, whereas deficits in rapid visual ability in children are primarily associated with problems in orthographic processing (Farmer & Klein, 1995). In contrast to the children, the adults showed a strong relation between rapid auditory ability and both orthographic and phonological processing. These results suggest that continued deficits in auditory ability may have a pervasive and negative impact on word processing in general. In addition, adults did not exhibit a relation between rapid visual ability and orthographic-processing problems. Orthographic-processing deficits may

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result from a reading delay condition that can be overcome with increased reading exposure (Harm & Seidenberg, 1999).

Many correlational and training studies have shown that later reading achievement is predicted best by earlier phonological knowledge, as measured by phoneme segmentation, phoneme deletion, and phoneme blending (Wagner, Torgesen, & Rashotte, 1994). In fact, attempts at phonological decoding during reading may be the main learning mechanism that brings about knowledge of whole word spellings (Jorm & Share, 1983). Indeed, some have suggested that phonological decoding from letters to sounds may be a "self-teaching device" that functions to establish orthographic representations and, hence, an autonomous orthographic lexicon (Share & Stanovich, 1995). Thus, phonological processes not only have a causal role in later word decoding ability (Wagner et al., 1994), but may also serve to increase the representational properties of words as they are actually read. Taken together, this research suggests that deficits in phonological processing may be the marker characteristic of reading disability. However, there is also clear evidence that some children with reading problems have difficulty in learning the orthographic spelling patterns of English (Castles & Coltheart, 1993). Children with reading problems are not a homogeneous group, but rather a heterogeneous group including individuals with distinct behavioral deficits that may result from different etiologies.

DIFFERENTIAL DEVELOPMENT MODEL OF READING DISABILITY

There is debate in the literature over what underlies individual differences in orthographic and phonological processing. Some investigators claim that reading and oral-language disabilities in children are caused by a low-level deficit in rapid temporal perception. In fact, studies show that reading disabilities are associated with the inability to represent rapidly presented visual stimuli (Eden, Stein, Wood, & Wood, 1995) and that oral-language disabilities are associated with the inability to represent rapidly presented auditory stimuli (Tallal et al., 1996). Tallal (1980) and colleagues argued that children with oral language impairment suffer from a problem in processing rapid temporal changes in speech. This deficit may result in the inability to form accurate representations of phonemes that may eventually result in a phonemic awareness deficit and then reading disability.

Within the field of reading, a transient system deficit in the magnocellular stream was implicated in readers with impairments (Lovegrove, Martin, & Slaghuis, 1986). The magnocellular system is important for processing stimuli that change rapidly over time, such as moving objects, whereas the parvocellular system is important for processing location, color, and orientation. The parvocellular system is clearly involved in reading because letter and word recognition require the analysis of location and orientation, but individuals with dyslexia appear to not have abnormalities in the parvocellular system. Indeed, physiological studies of deceased individuals with dyslexia have revealed abnormalities only in magnocellular neurons in the lateral and medial geniculate nucleus, which are involved in visual and auditory processing, respectively (Galaburda, Menard, & Rosen, 1994; Livingstone, Rosen, Drislane, & Galaburda, 1991). Imaging studies also show less activity in V5/MT when individuals with dyslexia are processing moving stimuli (Eden et al., 1996), and the amount of activity in V5/MT (extrastriate visual area) is related to reading rate in individuals with dyslexia (Demb, Boynton, & Heeger, 1998). This visual deficit may result in increased "persistence" of stimuli in the visual system, and therefore, the reader with impairment may not be able to effectively inhibit past visual word forms to accurately perceive new visual word forms when reading text. This persistence disrupts normal reading acquisition and may slow the acquisition of low-frequency exception words. A recent model of reading disabilities (Farmer & Klein, 1995) suggested that rapid visual perception deficits may lead to *orthographic* problems, whereas rapid auditory perception deficits may lead to *phonological* problems. Figure 1 displays the differential development model of reading disability that suggests deficits in visual temporal processing should be primarily related to orthographic problems in children, whereas auditory ability deficits should be primarily related to phonological problems in children and adults.

These orthographic and phonological deficits in children with reading disabilities may correspond to the two types of dyslexia discussed in the developmental literature (Castles & Coltheart, 1993; Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1995; Stanovich, Siegel, & Gottardo, 1997). Individuals with *surface* dyslexia have deficits in orthographic processing, such as in naming exception words and in spelling tasks. Individuals with *phonological* dyslexia have deficits in phonological processing, such as in naming nonwords and in making phonetic judgments. Note that these subtypes of children tend to have relative deficits in orthographic or phonological processing. Overall, individuals with dyslexia are impaired at exception word and nonword reading relative to readers without impairment.

There are at least three potential levels of perceptual deficits in reading disability (Farmer & Klein, 1995). The first level is the *detection* of a single stimulus. Detection requires the determination of the presence or absence of a stimulus. The literature provides little evidence for auditory or visual deficits in this very low level perceptual ability in readers with impairment (Blackwell, McIntyre, & Murray, 1983; Tallal, 1980). The lack of deficits in the detection task is crucial to the hypothesis that readers with impairment have a temporal-processing deficit because the detection task does not require temporal perception. The second level is the *individuation* of two stimuli. Individuation requires the determination of the existence of two stimuli with a very short interstimulus interval (ISI). The litera-

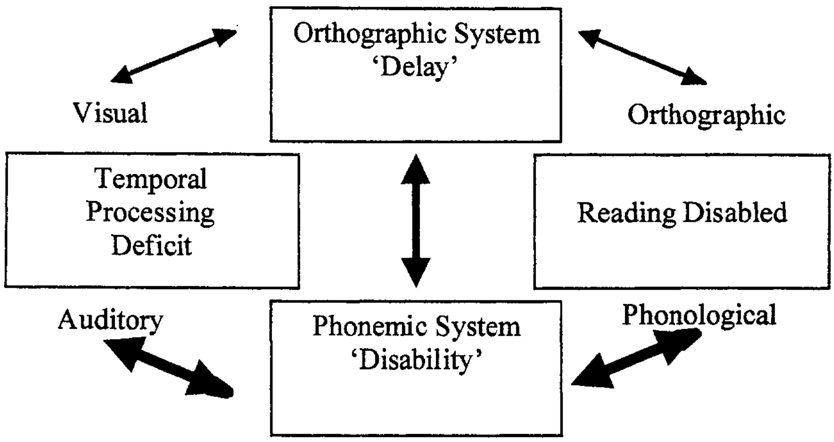

FIGURE 1 A differential development model of reading disability that suggests deficits in rapid visual temporal processing are primarily related to orthographic problems, whereas rapid auditory ability deficits are primarily related to phonemic problems. The narrow arrows in the visual–orthographic pathway represent that this is a reading delay condition that can diminish in adulthood. The wide arrows in the auditory–phonemic pathway represent that these problems often persist into adulthood. The arrows in the figure are bidirectional because we assume that higher levels of processing can influence lower levels of processing and vice versa. The phonemic system is connected to the orthographic system by a bidirectional arrow to represent that persistent deficits in phonological processing may negatively impact orthographic processing. This model is based loosely on ideas in Farmer and Klein (1995) and Harm and Seidenberg (1999).

ture shows some evidence for visual deficits, but little evidence for auditory deficits, in readers with impairment in the individuation tasks (McCroskey & Kidder, 1980; Slaghuis & Lovegrove, 1985). However, more recent studies have questioned the relation between dyslexia and individuation ability as measured by visual flicker and spatial frequency tasks (Victor, Conte, Burton, & Nass, 1993; Walther-Mueller, 1995). The third level is the *temporal ordering* of two or more stimuli. This requires the reader to report the order of stimuli presented in a sequence. For example, in one auditory temporal-ordering task, the participant is required to report aloud the sequence of three high or low pure tones. Temporal-ordering tasks are more demanding than the previous two levels because these tasks require an accurate representation of stimuli and short-term memory processes. The literature provides strong evidence for auditory deficits in temporal ordering and some evidence for visual deficits in readers with impairment (Brannon & Williams, 1988; Tallal, 1980). When taken together, this research suggests that reading disability should be related to deficits in visual individuation and both visual and auditory temporal ordering.

Most of the aforementioned studies have investigated nonspeech stimuli, such as pure tones. There has been some controversy in the literature as to whether speech represents a specialized area of auditory processing (Liberman, 1982; Liberman & Mattingly, 1985). A review of the literature concluded that readers with impairment have deficits in detection, individuation, and temporal-ordering tasks when speech stimuli are used (McBride-Chang, 1995). As discussed earlier, the research on nonspeech stimuli suggests limited deficits in detection and individuation, but the research on speech stimuli seems to suggest deficits at these levels. One of the most studied individuation tasks in individuals with dyslexia is categorical speech perception. These studies show that deficits in categorical perception may be weak (Werker & Tees, 1987) and apply only to a subset of individuals with dyslexia—for example, those who have low phonological awareness (Manis et al., 1997). It may be that readers with impairment have deficits in accurately representing phonetic factors (articulatory features), but they are not impaired at perceiving rapid spectral changes (Mody, Studdert-Kennedy, & Brady, 1997).

THIS STUDY

The general approach of this study was to examine the relation between individual differences in perceptual ability and reading skill within a sample of children with reading impairment (Experiment 1) and adults with reading impairment (Experiment 2). This study examined the association of both rapid visual and rapid auditory ability with both orthographic and phonological processing. No previous study has included an examination of the relation among all of these component processes (Reed, 1989). However, all of these component processes must be examined to provide a proper test of the differential development model of reading disability presented in Figure 1. A failure to obtain the predicted correlations of sensory-processing deficits with orthographic and phonological deficits would invalidate the differential development model. However, the correlational nature of this study makes it impossible to reach any conclusions regarding causal mechanisms. Indeed, it may be difficult to determine causality because perceptual and word-processing components are likely to be interactive (McClelland & Rumelhart, 1981). Computational modeling as well as animal studies clearly show that there is an interaction between high- and low-level processing. Studies with male rats have shown that cortical lesions result in fewer large and more small neurons in the medial geniculate nucleus and an accompanying deficit in fast auditory temporal processing (Herman, Galaburda, Fitch, Carter, & Rosen, 1997).

This study employed naming and priming tasks to measure orthographic and phonological processing. We realize that all reading measures require both orthographic and phonological knowledge; however, these components of processing may be differentially weighted in particular tasks. We chose exception word naming as a measure of orthographic processing and nonword naming as a measure of phonological processing because these have been used in previous studies on subtypes of reading disorders (Castles & Coltheart, 1993). Exception word reading requires knowledge of spelling patterns that violate statistical regularities in English, whereas nonword reading requires generalization of knowledge about phonological structure to unfamiliar nonwords. The priming task used the brief duration identification paradigm (Perfetti, Bell, & Delaney, 1988). This task allows an assessment of the magnitude of orthographic and phonological priming. This paradigm requires the participant to write down a very briefly presented target (e.g., 60 ms) displayed after a briefly presented (60 ms) orthographic or phonological prime. In a previous investigation of readers without impairment, Booth, Perfetti, and MacWhinney (1999) reported that good readers (second through sixth graders) exhibited more phonological and orthographic priming than did poor readers. Because these stimuli were displayed for a duration (less than 60 ms) that was brief enough to prevent complete processing, this suggests that good readers activate orthographic and phonological information more quickly and automatically than do poor readers. This study established the utility of the brief duration identification paradigm for examining reading skill differences in orthographic and phonological priming.

EXPERIMENT 1

Experiment 1 examined the relation of visual and auditory perceptual ability to orthographic and phonological processing in a population of children with reading impairment. We expected these low-ability children with reading impairment to have difficulty in processing phonological as well as orthographic representations. Apart from this overall deficit, we expected rapid visual ability to be uniquely associated with orthographic-processing deficits and rapid auditory ability to be uniquely associated with phonological-processing deficits. This pattern of relations should be reflected in the naming and possibly in the priming tasks. These findings would be consistent with the differential development model presented in Figure 1.

Method

Participants

Participants were 35 children (M = 15.2 years, range = 11–18 years) from an educational program for children with specific learning disabilities in the Pittsburgh metropolitan area. Only children with at least a second-grade proficiency in reading, based on their scores on the Word Identification subtest (Woodcock, 1987) were chosen. The participants could not complete the experimental tasks without this level of proficiency in reading. All participants had been administered the Wechsler Intelligence Scale for Children (Wechsler, 1991) within the last 5 years. The mean Full IQ was 80 (range = 65–109)—4 children had an IQ score below 70, and 10 children had an IQ score between 70 and 80. All children also had existing neuropsychological examinations from registered clinical psychologists. The most common *Diagnostic and Statistical Manual of Mental Disorders* (4th ed. [*DSM–IV*]; American Psychiatric Association, 1994) diagnoses were Cognitive Disorder (43%), Borderline Intellectual Functioning (39%), Reading Disorder (37%), Mathematics Disorder (19%), Writing Disorder (21%), and Attention Deficit Hyperactivity Disorder (24%). No children had diagnosed behavior or emotional problems according to school records. In addition, no children had motoric problems that interfered with their ability to complete the experimental protocol.

We realize that there is controversy over how to define the population that has reading impairments. Some researchers argue that there must be a significant discrepancy between reading achievement and IQ, whereas others argue that there need not be a discrepancy for a child to have a learning disability in reading (Shaywitz, Fletcher, & Shaywitz, 1994; Stanovich & Siegel, 1994). There is some research suggesting that children with reading impairment who are with and without an IQ discrepancy behave in similar ways (Shaywitz, Fletcher, Holahan, & Shaywitz, 1992; Siegel, 1992). In our view, the inclusion of children who have low IQ scores and who lack the IQ discrepancy makes our findings more general in that the results of the study appear to apply to a larger population of children and adults. However, the inclusion of many children with low IQ scores may make it difficult to compare the results of this study to other studies of children with reading disorders who have IQs in the normal range. Nevertheless, to make sure that the results of our study were not caused by age or IQ differences, we examined the relation of auditory and visual perceptual ability with orthographic and phonological processing after partialling for age and IQ.

Materials and Procedure

All materials administered to the participants were presented on identical 15-in. MultiScan Macintosh monitors controlled by a Macintosh PowerPC computer. All tasks described hereafter were presented with PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993), and responses were recorded with the CMU button box.

Rapid visual. The participant was asked to fixate on a cross in the middle of the computer screen about 50 cm away. After the participant pressed a button on a button box, four to nine black dots flashed one after the other at the same place on a white computer screen. The end of the series was marked by a number line (3 to 10) presented on the bottom of the screen. After the participant saw the number line, he or she was asked to report orally the number of dots. The experimenter entered the number reported by the participant into the computer. Each dot was .167 × .167 in. and was presented for 40 ms. The interstimulus intervals were 200, 300, or 400 ms. There were 9 practice trials and 72 test trials, so this meant that there were 24 test trials at each interstimulus interval.

This rapid visual task was used because performance on a similar version was shown to be related to reading problems (Eden et al., 1995). We considered the rapid visual task to be primarily an individuation task because it required the participant to detect gaps between the same visual stimuli (Farmer & Klein, 1995). However, this task may have also had other cognitive components that contributed to performance. For example, some children may have used a counting strategy in which they retrieved number names and internally articulated them. At the very least, this task had a short-term memory component because it required participants to remember the number of dots presented and then to report that number to the experimenter. However, we argue that if the memory component of this task was responsible for the effects discussed later, then there is no reason to predict why rapid visual ability should be associated only with visual orthographic and not with visual phonological processing.

Rapid auditory. The participant was asked to listen to a series of two or three tones. The participant controlled the presentation of each trial with a button box. The end of each trial was marked by an "enter order" prompt on the computer screen. The participant was then asked to report aloud the sequence of tones to the experimenter, who then entered the sequence into the computer (e.g., HLH for high, low, high). The pure tones were digitized for presentation by computer through headphones. The tones were either 100 or 300 Hz, with a 75- or 150-ms duration and an interstimulus interval of 100 or 300 ms. All tones faded in and out for 20 ms. All possible combinations of frequencies, duration, and interstimulus intervals were presented randomly. No feedback was given during the test session (64 trials), although during the practice session (12 trials) the experimenter provided feedback until the participant could accurately discriminate between the high and low tones. The practice session contained the easier two-tone sequences with long durations (225 ms) and long ISIs (450 ms).

This rapid auditory task was used because a similar version has been shown to be related to oral-language problems (Tallal & Piercy, 1973, 1974, 1975). We considered the rapid auditory task to be primarily a temporal ordering task because it required the participant to report the sequence of different stimuli (Farmer & Klein, 1995). However, this task also had a short-term memory component because it required the participants to remember the order of tones presented. Some participants may have also internally rehearsed the articulatory code for the tone labels. However, we argue that if the memory component of this task was responsible for the effects discussed later, there is no reason to predict why rapid auditory ability should be associated only with visual phonological and not with visual orthographic processing.

Standard words. The Word Identification subtest (Woodcock, 1987) contains approximately 80% regular words and 20% irregular words. The test begins with easy words, such as *play*, and ends with more difficult words, such as *Zeitgeist*. Test administration was stopped when the participant pronounced six consecutive words incorrectly. This test was used to measure general reading skill.

Nonwords. The Word Attack subtest (Woodcock, 1987) is a nonword naming measure containing items that range in complexity from easy words at the beginning, such as *dat*, to more difficult words at the end, such as *byrcal*. Participants read all nonwords in this task regardless of their accuracy. We considered this task to primarily measure phonological-processing skill.

Exception words. The Exception Words subtest (Adams & Huggins, 1985) requires the participant to read aloud 45 exception words. The items range from easy words, such as *ocean*, to more difficult words, such as *baroque*. Participants read all exception words in this task regardless of their accuracy. We considered this task to primarily measure orthographic-processing skill.

Orthographic and pseudohomophone priming. This task involved 15 practice trials followed by a series of 120 test trials. A fixation cross was displayed before each trial, and the participant was asked to press a button to begin each trial. Each trial consisted of a brief presentation of a nonword prime (60 ms), followed immediately by a brief presentation of a real word target (60 ms), which was then immediately followed by a mask of the form XXXXX (500 ms). There was no interstimulus interval between prime and target or between target and mask. Primes were always presented in uppercase, and targets were always presented in lowercase, so that any observed priming effects would have to be attributed to an abstract letter representation and not a lower level case-specific visual representation. The pattern mask was used to disrupt the processing of the target. Without the pattern mask, performance on this task would have been near ceiling for the more advanced readers because of luminance persistence of the target on the computer monitor. All stimuli were presented in white letters on a black background in 16-point Courier font. All words were four (1.6 cm) or five (2 cm) letters in length. The participants' task was to write down the target word after each practice and test trial. The dependent variable on this task was the percentage of correct responses. Reaction time was not measured in this task because factors not associated with orthographic and phonological processing were likely to influence writing time—for example, the amount of time to move pencil to the proper location on paper. Participants were encouraged to guess about the identity of the target if they were not sure. No partial credit was given. We are assuming that the participants' written responses reflected access to orthographic and phonological forms, although other factors, such as knowledge of common letter patterns, may have influenced the translation from a mental representation to a written word.

There were one within-item and two between-item factors in the priming task. The within-item factor varied the three prime types. The pseudohomophone primes were phonologically identical to the targets (e.g., *TUME–tomb*). The orthographic primes shared the same overlapping letters with the target words as pseudohomophone primes but different nonoverlapping letters (e.g., *TAMS–tomb*). The control primes shared no letters in common with target (e.g., *USAN– tomb*). There were three counterbalancing lists, so that across participants, each prime preceded each target an equal number of times. This meant that the three groups of participants corresponding to the three counterbalancing lists received a different list of prime–target pairs.

The two between-item factors were (a) orthographic similarity between prime and target and (b) target frequency. Orthographic similarity was defined on the basis of the formula that takes into account identical letters in the same position, in adjacent positions, and in the first and final positions (Van Orden, Johnston, & Hale, 1988). Our orthographic similarity value (*os* = .52) was exactly the same for the orthographic and pseudohomophone primes and was similar to, but slightly lower than, those found in other studies (e.g., *os* = .62–.68; Van Orden et al., 1988). *TUME–tomb* is an example of a low orthographic similarity pair, whereas *HOAP–hope* is an example of a high orthographic similarity pair. The low-frequency words had a mean frequency level of 11.5 in 1 million. The high-frequency words had a mean frequency level of 167 in 1 million (Kucera & Francis, 1967).

Results and Discussion

The following analytical procedure was used for Experiment 1 with children with reading impairment and later for Experiment 2 with adults with reading impairment. First, we examined the relation of a number of stimuli, duration, and interstimulus interval to accuracy levels in the rapid temporal ability tasks. Second, we examined individual differences in naming accuracy on the exception word and nonword tasks, and then we examined the relation among overall naming accuracy and orthographic and phonological priming. Finally, we examined the relation between rapid temporal ability and orthographic and phonological processing.

Rapid Temporal Processing

Figure 2 displays accuracy on the rapid visual ability measure as a function of the number of dots in the set and the ISI between each dot in the set. A 6 (dot number: 4, 5, 6, 7, 8, 9) × 3 (dot ISI: 200, 300, 400 ms) analysis of variance (ANOVA) yielded significant main effects for dot number, $F(5, 629) = 3.35, p < .05$; dot ISI, $F(2, 629) = 46.12, p < .001$; and a trend for a significant interaction between dot number and dot ISI, $F(10, 629) = 2.60, p < .10$. The main effects show that sets with a greater number of dots or with shorter ISIs had lower accuracy levels than did sets with a fewer number of dots or with longer ISIs, respectively. However, the interaction suggests that increasing the number of dots at the long ISIs had a minimal effect on accuracy, whereas increasing the number dots at the shorter ISIs reduced accuracy levels substantially.

Figure 3 displays accuracy on the rapid auditory ability measure as a function of the number of tones in the set, the duration of the tones in the set, and the ISI between each tone in the set. A 2 (tone number: 2, 3) × 2 (tone duration: 75, 150 ms) ×

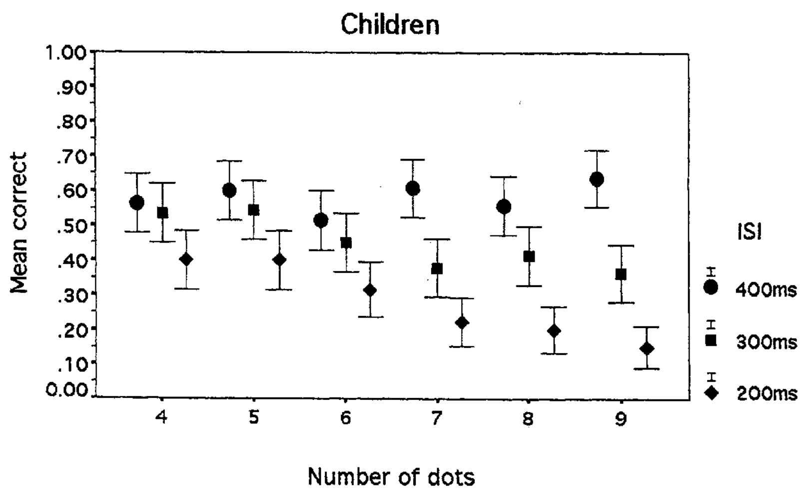

FIGURE 2 Mean correct on the rapid visual ability measure as a function of the number of dots in the set (4 to 9) and the ISI between each dot in the set (200, 300, or 400 ms) for the children in Experiment 1. Error bars indicate one standard error.

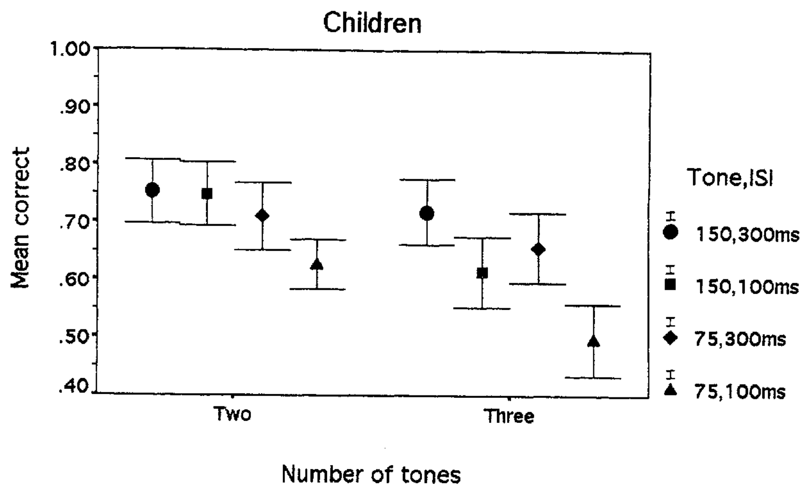

FIGURE 3 Mean correct on the rapid auditory ability measure as a function of the number of tones in the set (2, 3), the duration of the tones in the set (75, 150 ms), and the ISI between each tone in the set (100, 300 ms) for the children in Experiment 1. Error bars indicate one standard error.

2 (tone ISI: 100, 300 ms) ANOVA yielded a significant main effect for tone number, $F(1, 279) = 8.27, p < .01$; tone duration, $F(1, 279) = 7.49, p < .01$; and tone ISI, $F(1, 279) = 8.70, p < .01$. These main effects indicate that sequences of two tones had higher accuracy levels than sequences of three tones, that sequences of long tones had higher accuracy levels than sequences of short tones, and that sequences with long ISIs had higher accuracy levels than sequences with short ISIs.

For the remaining analyses involving rapid temporal or auditory ability, we used an average measure, including all items in each instrument, because increasing the number of items increased the reliability of the measure. This was justified because the correlations between the subscales in the temporal ability measures were high ($r_{ave} = .69$). By subscales, we mean accuracy levels on each combination of number, duration, and ISI factors.

Individual Differences in Word Naming

Table 1 displays the means for the word naming, rapid temporal ability, and IQ measures for the children with reading impairment. We were interested in whether the children had particular deficits on the exception words or nonwords measures, so we calculated difference scores (*d*) between exception words and standard words and between nonwords and standard words. These difference scores give an estimate of the children's relative deficits in orthographic and phonological pro-

TABLE 1
Means and Standard Deviations for Word Naming, Rapid Temporal, and IQ Measures in Experiment 1 for the Children Who Were Reading Impaired

	M	*SD*
Naming		
Standard words	50.9	18.4
Exception words	38.1	28.1
Nonwords	34.7	24.1
Rapid temporal		
Visual	43.6	21.1
Auditory	66.6	23.2
IQ		
Verbal	81.9	15.7
Performance	78.5	13.9

Note. Means for the naming and rapid temporal measures are percentages. Means for the IQ scores are standard scores ($M = 100$, $SD = 15$).

cessing. The difference scores for orthographic ($d = 12.8$) and phonological processing ($d = 16.2$) were not significantly different, $t(34) = 1.12$, $p = .27$, suggesting that the children with reading impairment were having difficulty with phonological as well as with orthographic processing.

All analyses on the standard words and nonwords measures were calculated on the raw scores, even though normative data are available for these measures (Woodcock, 1987). This was done because the normative data are not sensitive for the adult populations in Experiment 2 for two reasons. First, the normative sample only included adults up to 33 years of age; second, there are a limited number of words on the upper end of the range of item difficulties. Nevertheless, we computed percentile ranks, standard scores, and age equivalents on the standard words measure for the reading disabled children in Experiment 1 and the reading disabled adults in Experiment 2 (see Appendix). These calculations show that on average the children and adults scored lower than the 13th percentile in word naming. Clearly, both children and adults in this study were severely reading disabled. These figures also suggest that the adults sampled may be slightly less disabled than the children sampled, but these scores must be interpreted with caution because they are not sensitive to older populations.

Orthographic and Phonological Priming

In the priming analyses, naming accuracy was the one between-participant variable. Naming accuracy was treated as a continuous regressor variable to more accurately represent underlying differences in ability. Because this design requires an analysis focusing on a continuous participant variable, only participant analyses could be computed. Naming accuracy was defined as the mean score on the three naming measures—standard words, exception words, and nonwords. All three naming measures were highly intercorrelated: standard–exception, $r(34) = .94, p < .001$; standard–non, $r(34) = .82, p < .001$; exception–non, $r(34) = .77, p < .001$. Thus, combining them was a reasonable approach.

There were two within-participant independent variables—orthographic similarity and word frequency. On the basis of a previous study of children without disabilities (Booth, Perfetti, & MacWhinney, 1999), we expected the priming effects to depend on the amount of orthographic overlap of the prime with the target and on the frequency of the target. In particular, we expected more orthographic priming for pairs with high orthographic similarity and for high-frequency targets.

There were two dependent variables of interest in the priming task—orthographic priming and pseudohomophone priming. Orthographic priming was calculated as the difference (d) between accuracy in the orthographic and control conditions. Because the orthographic primes had overlapping letters and sounds with the target, we must attribute these priming effects to a combination of orthographic and phonemic overlap. Pseudohomophone priming was calculated as the difference (d) between accuracy in the pseudohomophone and orthographic conditions. Because the pseudohomophone primes had the same level of orthographic similarity to the targets as did the orthographic primes, it is possible to view the pseudohomophone priming effects as resulting purely from phonological priming. Planned comparisons were computed separately for the orthographic and pseudohomophone priming dependent variables, and these results are presented in different sections.

In summary, orthographic and pseudohomophone priming difference scores were submitted to a 2 (orthographic similarity: high, low) × 2 (frequency: high, low) analysis of covariance (ANCOVA) with naming accuracy as an independent regressor variable. All data are presented as if naming accuracy were a dichotomous variable (median split) for clarity of presentation and ease in interpretation, but all statistical analyses used the continuous naming accuracy variable. Figure 4 displays accuracy levels for the three priming conditions for the high and low naming accuracy scores of children.

Pseudohomophone priming. As predicted, the most important finding was that children with high naming accuracy scores benefited more from pseudohomophone priming ($d = 5.4\%$) than did children with low naming accuracy scores ($d = -1.7\%$), $F(1, 139) = 9.12, p < .01$. Presumably, the children with high naming accuracy scores had quicker access to higher quality phonological representations, which allowed them to use this information for target identification more efficiently than the children with low naming accuracy scores. We have ar-

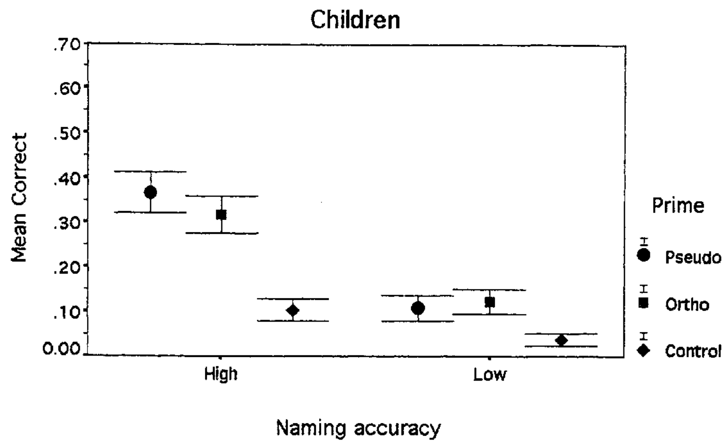

FIGURE 4 Mean correct for the pseudohomophone (phonological), orthographic, and control priming conditions for the high and low naming accuracy scores of children in Experiment 1. Error bars indicate one standard error.

gued elsewhere that the more precise and redundant (Perfetti, 1992) lexical representations of better readers who do not have impairment allow them to more efficiently activate representations for words and grapheme–phoneme correspondences at these very short presentation durations, and this results in larger priming effects (Booth et al., 1999). This relation held in the this experiment even though our sample was of children who have severe reading impairment.

Orthographic priming. As predicted, children with high naming accuracy scores also exhibited more orthographic priming (d = 21.4%) than did the children with low naming accuracy scores (d = 8.1%), $F(1, 139) = 36.20, p < .001$. In addition, high orthographic similarity pairs (d = 18.9%) benefited more from priming than did low orthographic similarity pairs (d = 11.0%), $F(1, 139) = 8.78, p < .01$. The high similarity pairs showed more priming because the larger amount of letter overlap allowed orthographic information to influence processing to a greater degree. Finally, high-frequency targets (d = 19.0%) benefited more from orthographic priming than did low-frequency targets (d = 10.9%), $F(1, 139) = 9.25, p < .01$. This can be accounted for by a model of word recognition that assumes that high-frequency targets are driven more strongly by orthographic input because of their increased frequency of exposure (Plaut, McClelland, Seidenberg, & Patterson, 1996). Stronger input for high-frequency targets means that less priming information is needed to produce correct identification. Low-frequency targets are not driven strongly by orthographic input, so more priming information is needed to produce correct identification.

Comparison of Readers With Impairment to Reading Matched Control Population

The data from a group of control children were taken from a separate study that examined the development of orthographic and phonological knowledge (Booth et al., 1999). The control children were not part of this study, so we have a limited number of measures on these children. Our measures included age, phonological priming, orthographic priming, and word naming ability. The control children were matched to the children with reading impairment in terms of their standard word naming ability on Word Identification (Woodcock, 1987). The means on word naming for the control group ($M = 49.5$, $SD = 18.2$) and group of individuals with reading impairment ($M = 45.6$, $SD = 19.9$) were not significantly different, $t(69) = 1.23, p = .22$. Because these groups were matched based on reading age, the mean chronological age of the control children ($M = 9.2$ years, range = 7–11 years) was significantly less than the mean age of the readers with impairment ($M = 15.2$ years, range = 11–18 years), $t(69) = 13.81, p < .001$.

Figure 5 displays the accuracy levels for the priming conditions for the children with reading disabilities and for reading-age-matched children without disabilities. To compare the accuracy levels of these two groups, a 2 (group: nondisabled, disabled) × 3 (prime: pseudohomophone, orthographic, control) ANOVA was computed. This analysis yielded significant main effects for group, $F(1, 209)$ =

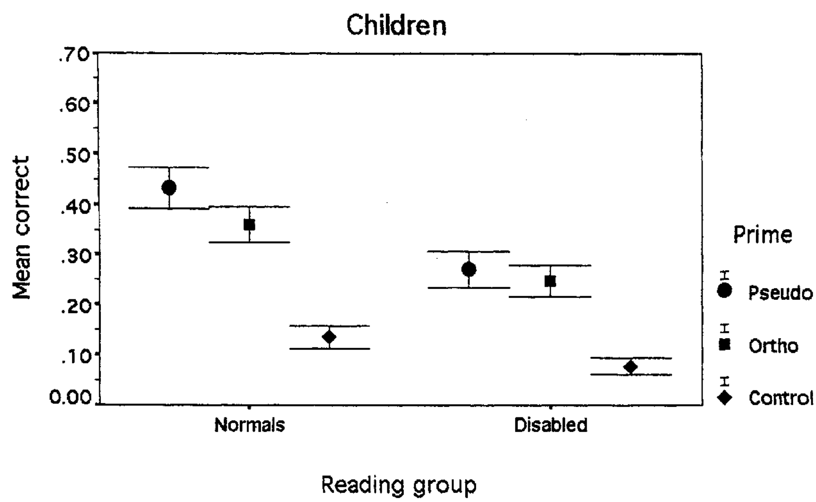

FIGURE 5 Mean correct for the pseudohomophone (phonological), orthographic, and control priming conditions for the children with reading disabilities in Experiment 1 and for reading-age-matched children without disabilities. Error bars indicate one standard error.

18.85, $p < .001$, and for prime, $F(1, 209) = 34.82, p < .01$. Even though the readers with disabilities were matched to the children without disabilities in standard word reading, the readers with disabilities (19.9%) exhibited significantly lower overall accuracy levels than did those without disabilities (30.9%). This suggests that readers with disabilities cannot quickly and automatically activate consistent information between the prime and the target, or that they show more interference from the inconsistent information between the prime and target.

The lack of a significant Group × Prime interaction, $F(1, 209) = 1.39, p = .25$, suggests that both groups exhibited a similar amount of priming. A closer examination of the means presented in Figure 5, however, reveals a trend for the reading-age-matched children without disabilities to show more phonological priming (pseudohomophone – orthographic) than the readers with disabilities. Taken together, these results suggest that the readers who have impairments were not qualitatively different from the controls without disabilities, but rather the readers with impairment were just quantitatively delayed in their development of orthographic to phonological correspondences.

Relation of Rapid Temporal With Orthographic and Phonological Processing

Table 2 displays the results of the hierarchical regression equations predicting accuracy on the standard words, exception words, and nonwords measures. We first entered age and then IQ into the equation to partial out these effects so that the predictive power of the rapid perceptual measures could not be attributed to differences in age or IQ. Indeed, these analyses showed that both age and IQ explained unique variance in word naming, Then we determined whether rapid auditory abil-

TABLE 2
Hierarchical Regression Equations Predicting Accuracy (Multiple R) on the Three Naming Tasks in Experiment 1 for the Children Who Were Reading Impaired

	Standard Words	*Exception Words*	*Nonwords*
Age	.37*	.42*	.31*
IQ	.46*	.53*	.51*
Rapid visual	.65*	.73*	.61*
Rapid auditory	.70	.73	.71*
Rapid auditory	.65*	.62*	.70*
Rapid visual	.70	.73*	.70

*$p < .05$ for the unique variance explained by that variable when entered into the equation. Age then IQ were entered into the equation. Next, either rapid visual then rapid auditory or rapid auditory then rapid visual were entered into the equation.

ity explained unique variance in naming accuracy after partialling for rapid visual ability. Finally, we determined whether rapid visual ability explained unique variance in naming accuracy after partialling for rapid auditory ability. These analyses showed that rapid visual ability explained unique variance in orthographic processing as measured by exception words naming, $t(34) = 3.02, p < .01$, but not in phonological processing as measured by nonword naming, $t(34) = 0.40, p = .67$. Conversely, rapid auditory ability explained unique variance in phonological processing, $t(34) = 2.69, p < .05$, but not in orthographic processing, $t(34) = 0.70, p = .48$. These results support the differential development model of reading disability presented in Figure 1, which argues orthographic-processing problems are associated primarily with rapid visual ability deficits, whereas phonological-processing problems are associated primarily with rapid auditory ability deficits.

The rapid perceptual measures explained unique variance in orthographic or phonological processing despite the fact that rapid visual and rapid auditory ability were significantly correlated, $r(34) = .59, p < .001$. Furthermore, the rapid perceptual measures explained common variance in orthographic and phonological processing. This may be due to more general abilities shared by the rapid perceptual tasks, such as processing speed or attention.

We also examined the unique variance explained by rapid auditory and rapid visual ability in the magnitude of orthographic and phonological priming. Table 3 displays the results of the hierarchical regression equations predicting orthographic and phonological priming. These analyses show that rapid auditory ability explained unique variance in the magnitude of phonological priming, $t(34) = 2.67$, $p < .05$, but not in orthographic priming, $t(34) = 0.27, p = .78$. These results are consistent with the differential development model presented in Figure 1. However, the differential development model was not supported by the finding that rapid visual ability did not explain unique variance in orthographic priming, $t(34) = 0.70, p = .49$. Rapid visual ability may not have explained unique variance in or-

TABLE 3
Hierarchical Regression Equations Predicting (Multiple *R*) Pseudohomophone and Orthographic Priming in Experiment 1 for the Children Who Were Reading Impaired

	Pseudohomophone Priming	*Orthographic Priming*
Age	.08	.37*
IQ	.15	.40
Rapid visual	.20	.46
Rapid auditory	.35*	.48
Rapid auditory	.35*	.47
Rapid visual	.35	.48

*$p < .05$ for the unique variance explained by that variable when entered into the equation. Age then IQ were entered into the equation. Next, either rapid visual then rapid auditory or rapid auditory then rapid visual were entered into the equation.

thographic priming because the orthographic primes are both orthographically and phonologically similar to the targets, as compared to the control primes. These null results warrant further research on the relation between rapid visual ability and orthographic priming.

EXPERIMENT 2

As discussed earlier, individuals with surface dyslexia tend to have deficits in orthographic processing, and individuals with phonological dyslexia tend to have deficits in phonological processing. A recent computational model of dyslexia suggests that there is a different pattern of orthographic and phonological deficits for adults than for children with reading disabilities (Harm & Seidenberg, 1999). This model argues that phonological dyslexia results from a pervasive deficit that is characterized by inaccurate, incomplete phonological representations, suggesting that, without intensive auditory and phonemic training, phonological deficits should persist into adulthood because developing accurate phonological representations requires fine-grained discrimination in rapid acoustic transitions during speech input (Tallal & Piercy, 1973, 1974, 1975). There is some evidence that training can increase auditory and phonemic discrimination in children with language impairment (Tallal et al., 1996) and in Japanese adults who initially could not discriminate between the /r/ and /l/ in the English language (McClelland, 1999). As mentioned earlier, deficits in speech perception tend to be weak (Werker & Tees, 1987) and apply only to a subset of individuals with dyslexia (Manis et al., 1997). In contrast to phonological dyslexia, the computational model argues that surface dyslexia results from slower learning or less reading exposure that is characterized by a reading delay (Harm & Seidenberg, 1999). This suggests that orthographic deficits should diminish by adulthood because of increased exposure to written language.

The notion that phonological deficits should persist into adulthood, whereas orthographic deficits should diminish by adulthood, is reflected in the differential development model presented in Figure 1 as thicker lines in the auditory–phonological route than in the visual–orthographic route. Indeed, behavioral research suggests that improvements in adults with reading impairment primarily involve gains in orthographic processing and not in phonological processing (Bruck, 1992; Pennington, Lefty, Van Orden, Bookman, & Smith, 1987). Adults with reading impairment may access word meanings based on visual features and spelling patterns but continue to have deficits in phonological processing.

Experiment 2 examined the relation of rapid visual and auditory ability with orthographic and phonological processing in a population of adults with reading impairment. On the basis of the differential development model presented in Figure 1, we predicted that the adults with reading impairment would be more impaired on the nonword naming measure of phonological processing than on the exception word naming measure of orthographic processing. The differential development model also predicts that initially an inefficient visual system should slow down the process of reading and the acquisition of a sight word vocabulary in children. This slow down should be primarily reflected in limited acquisition of low-frequency exception words. Later, an inefficient visual system should have less of an impact on reading because increasing exposure to written words should allow the acquisition of the low-frequency exception words. In other words, we predicted a relation between rapid visual ability and orthographic processing in children with reading impairment but not in adults with reading impairment. The differential development model also predicts that phonological-processing deficits should persist into adulthood and that there should continue to be a strong relation between rapid auditory ability and phonological-processing skill. In fact, deficits in auditory ability and phonological processing may eventually prevent the attainment of normal levels of orthographic-processing skill because of the interaction between the phonological and orthographic systems in reading development (Plaut et al., 1996). The self-teaching hypothesis discussed earlier also predicts a snowballing effect of early deficits in phonological decoding on later orthographic skill (Share & Stanovich, 1995). Therefore, the differential development model predicts that deficits in rapid auditory ability should be related to orthographic-processing problems in adults with reading impairment.

Method

Participants

Participants were 32 adults ($M = 34.7$ years, range = 19–51 years) from an educational program in the Pittsburgh metropolitan area for adults with specific learning disabilities. Only adults with at least a second-grade proficiency in reading, based on their scores on the Word Identification subtest (Woodcock, 1987) were chosen. All participants had been administered the Wechsler Adult Intelligence Scale (Wechsler, 1985) within the last 5 years. The mean Full IQ was 87 (range = 75–110)—10 adults had IQ scores less than 80. All adults also had existing neuropsychological examinations from registered clinical psychologists. The most common *DSM–IV* diagnoses (American Psychiatric Association, 1994) were Cognitive Disorder (50%), Borderline Intellectual Functioning (33%), Reading Disorder (28%), Mathematics Disorder (28%), Writing Disorder (17%), and Attention Deficit Hyperactivity Disorder (17%). No adults had diagnosed behavior or emotional problems, according to their records. In addition, no adults had motoric problems that interfered with their ability to complete the experimental protocol. This adult sample was very similar to the child sample in Experiment 1 except that the adults had a slightly higher mean Full IQ (87 vs. 80, respectively). These samples may have been very similar because both programs are administered by the same nonprofit organization and use similar criteria for admission into the program. Furthermore, many of the adults in this study were enrolled at some time in the children's program.

Materials and Procedure

The materials and procedure for the adults in Experiment 2 were exactly the same as for the children in Experiment 1.

Results and Discussion

Rapid Temporal Processing

Figure 6 displays accuracy on the rapid visual ability measure as a function of the number of dots in the set and the ISI between each dot in the set. A 6 (dot number: 4, 5, 6, 7, 8, 9) × 3 (dot ISI: 200, 300, 400 ms) ANOVA yielded significant main effects for dot number, $F(5, 575) = 5.43, p < .001$, and dot ISI, $F(2, 575) = 8.78, p < .001$. The main effects indicate that sets with a greater number of dots or with shorter ISIs had lower accuracy levels than did sets with a fewer number of dots or with longer ISIs, respectively.

Figure 7 displays accuracy on the rapid auditory ability measure as a function of the number of tones in the set, the duration of the tones in the set, and the ISI between each tone in the set. A 2 (tone number: 2, 3) × 2 (tone duration: 75, 150 ms) × 2 (tone ISI: 100, 300 ms) ANOVA yielded a significant main effect for tone duration, $F(1, 255) = 4.09, p < .05$, and tone ISI, $F(1, 255) = 8.33, p < .01$. These main effects show that long tones had higher accuracy levels than short tones and that long ISIs had higher accuracy levels than short ISIs.

As with Experiment 1, for the rest of the analyses involving rapid visual or auditory ability in Experiment 2, we used an average measure, including all the items in each instrument. The correlation between the subscales in the temporal-processing measures were high ($r_{ave} = .71$), and increasing the number of the items in the scale increased the reliability of the measure.

Individual Differences

Table 4 displays the means for the word naming, rapid temporal ability, and IQ measures for the adults with reading impairment. To determine relative deficits in orthographic and phonological processing, we calculated the same difference

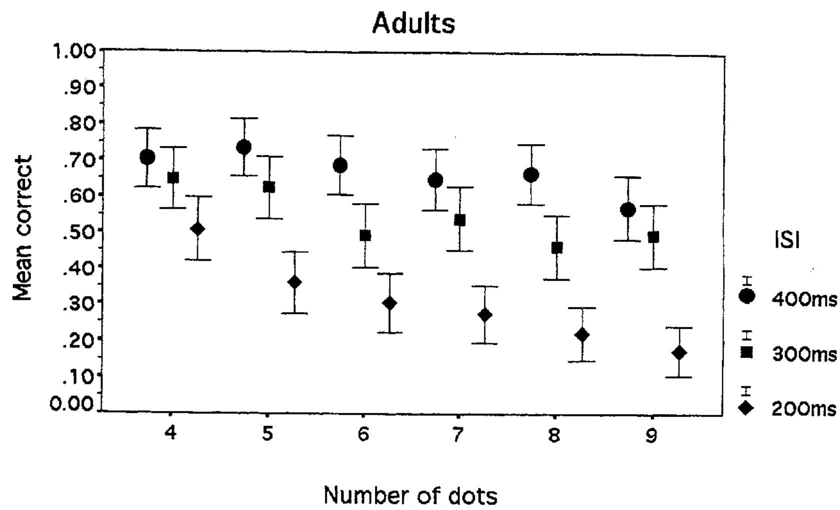

FIGURE 6 Mean correct on the rapid visual ability measure as a function of the number of dots in the set (4 to 9) and the ISI between each dot in the set (200, 300, 400 ms) for the adults in Experiment 2. Error bars indicate one standard error.

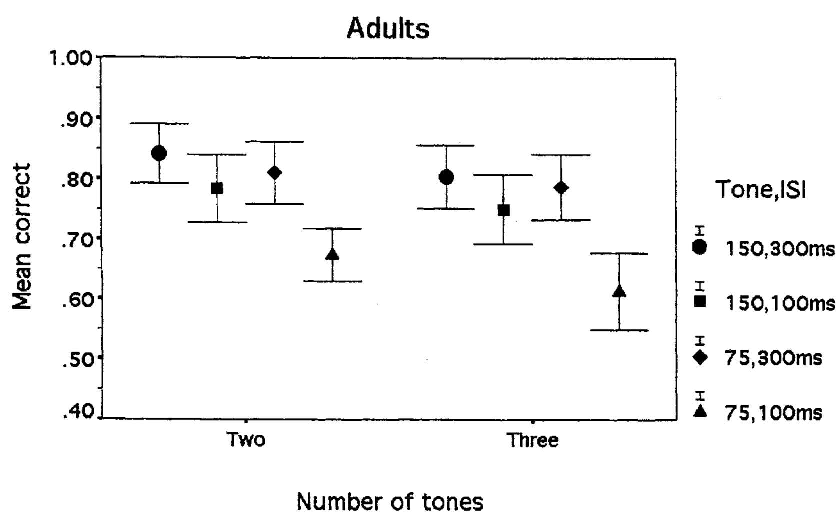

FIGURE 7 Mean correct on the rapid auditory ability measure as a function of the number of tones in the set (2, 3), the duration of the tones in the set (75, 150 ms), and the ISI between each tone in the set (100, 300 ms) for the adults in Experiment 2. Error bars indicate one standard error.

TABLE 4
Means and Standard Deviations for Word Naming, Rapid Temporal, and IQ Measures in Experiment 2 for the Adults Who Were Reading Impaired

	M	*SD*	*Child/Adult (%)*
Naming			
Standard words	71.2	12.4	71
Exception words	69.1	21.1	55
Nonwords	45.2	21.3	77
Rapid temporal			
Visual	50.5	21.3	86
Auditory	75.2	23.7	89
IQ			
Verbal	87.6	10.7	93
Performance	88.1	10.2	89

Note. Means for the naming and rapid temporal measures are percentages. Means for the IQ scores are standard scores ($M = 100$, $SD = 15$). Child/Adult is calculated as the percentage accuracy for children in Experiment 1 divided by the percentage accuracy for adults in Experiment 2. This measure provides an index of magnitude of the difference between children and adults.

scores (d) as those in Experiment 1. The adults in Experiment 2 had larger deficits on nonwords ($d = 26.0$) than on exception words ($d = 2.2$), compared to accuracy on the standard words measure, $t(31) = 8.52, p < .001$. The findings for adults with reading impairment were consistent with other studies that show a disproportionate improvement in orthographic processing, compared to phonological processing, with increasing reading exposure (Bruck, 1992; Pennington et al., 1987). This disproportionate improvement is in contrast to Experiment 1, which found that children with reading impairment performed equally poorly on the exception words and nonwords measures. Indeed, when accuracy levels in children and adults were directly compared, exception word accuracy in children was 55% of adult levels, whereas nonword accuracy in children was 77% of adult levels. These results support the differential development model presented in Figure 1, which argues that adults with reading problems may partially overcome deficits in orthographic processing.

Like the children in Experiment 1, the adults in Experiment 2 scored lower on the rapid visual measure than on the rapid auditory measure. Moreover, when the accuracy levels in children and adults were directly compared, it appears that development is marked by the same improvement in visual and auditory processing. Accuracy levels in rapid visual processing in children was 86% of adult levels, whereas accuracy levels in rapid auditory processing in children was 89% of adult levels. Unfortunately, the design of our study cannot determine whether the children or the adults have absolute deficits in temporal processing because our study did not include a control population that was given the rapid perceptual ability measures. However, it is likely that our child and adult samples did have absolute deficits because other studies that have used similar tasks have found deficits in populations with reading and oral language impairments (Eden et al., 1995; Tallal & Piercy, 1973, 1974, 1975).

Orthographic and Phonological Priming

As in Experiment 1, orthographic and pseudohomophone priming difference scores (*d*) were submitted to a 2 (orthographic similarity: high, low) × 2 (frequency: high, low) ANCOVA, with naming accuracy as an independent regressor variable. Naming accuracy was defined as the mean score on the three naming measures—standard words, exception words, and nonwords. All three naming measures were highly intercorrelated: standard–exception, $r(31) = .90, p < .001$; standard–non, $r(31) = .87, p < .001$; exception–non, $r(31) = .72, p < .001$. Figure 8 displays accuracy levels for the three priming conditions for the high and low naming accuracy adults.

Pseudohomophone priming. As predicted, adults with high naming accuracy scores ($d = 15.1\%$) benefited more from pseudohomophone priming than did

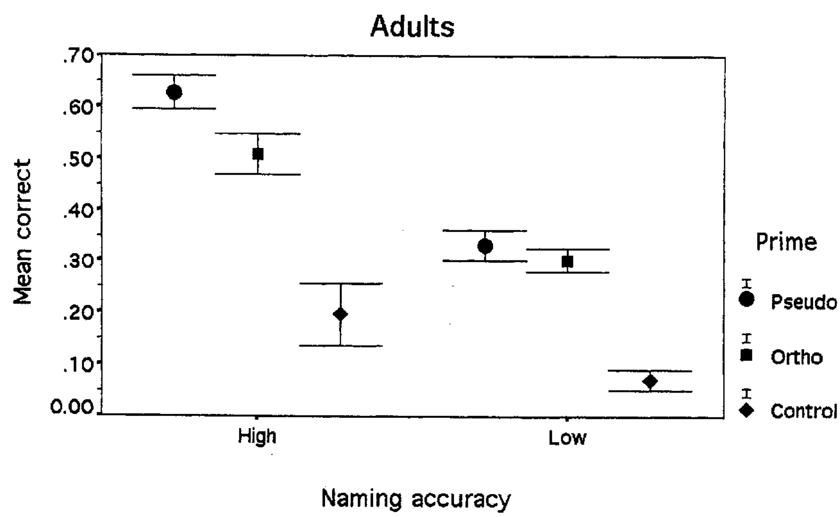

FIGURE 8 Mean correct for the pseudohomophone (phonological), orthographic, and control priming conditions for the high and low naming accuracy adults in Experiment 2. Error bars indicate one standard error.

adults with low naming accuracy scores ($d = 2.8\%$), $F(1, 127) = 9.91, p < .01$. The adults with high scores had quicker access to higher quality phonological representations allowed them to use this information for target identification more often than did the adults with low scores. This finding is consistent with the differential development model presented in Figure 1, which argues that there should be pervasive phonological-processing deficits in adults with severe reading problems.

Orthographic priming. In contrast to the ability differences for the children in Experiment 1, adults with high naming accuracy scores ($d = 29.4\%$) did not exhibit significantly more orthographic priming than did those with low naming accuracy scores ($d = 21.8\%$), $F(1, 127) = 1.15, p = .285$. This is consistent with the differential development model that argues orthographic deficits may be partially overcome in adult readers with impairments.

Like the children in Experiment 1, high orthographic similarity pairs (d = 35.8%) benefited more from orthographic priming than low orthographic similarity pairs ($d = 15.4\%$), $F(1, 127) = 35.97, p < .001$. In addition, high-frequency targets (d = 30.8%) benefited more from orthographic priming than did low-frequency targets ($d = 15.4\%$), $F(1, 127) = 9.32, p < .01$. See Experiment 1 for a discussion of these effects.

Relation of Rapid Temporal With Orthographic and Phonological Processing

As with Table 2 in Experiment 1, Table 5 displays the results of hierarchical regression equations predicting standard words, exception words, and nonwords naming. We found that rapid visual ability did not explain unique variance in

TABLE 5
Hierarchical Regression Equations Predicting Accuracy (Multiple *R*) on the Three Naming Tasks in Experiment 2 for the Adults Who Were Reading Impaired

	Standard Words	*Exception Words*	*Nonwords*
Age	.16	.07	.38*
IQ	.57*	.47*	.61*
Rapid visual	.58	.49	.63
Rapid auditory	.71*	.64*	.73*
Rapid auditory	.71*	.63*	.73*
Rapid visual	.71	.64	.73

*$p < .05$ for the unique variance explained by that variable when entered into the equation. Age then IQ were entered into the equation. Next, either rapid visual then rapid auditory or rapid auditory then rapid visual were entered into the equation.

orthographic processing, $t(31) = 0.66, p = .52$, or phonological processing, $t(31) = 0.30, p = .76$. This is not due to a ceiling effect or limited variability in performance on the rapid visual ability or naming measures. The adults exhibited levels of variability comparable to those of the children (see Tables 1 and 4). These results support the differential development model presented in Figure 1, which argues for the absence of a relation between rapid visual ability and orthographic processing in adults. In contrast to the findings with rapid visual ability, rapid auditory ability explained unique variance in both orthographic processing, $t(31) = 2.80, p < .01$, and phonological processing, $t(31) = 2.84, p < .01$. These results also support the differential development model that argues orthographic- and phonological-processing problems in adults with reading impairment should be associated with deficient rapid auditory ability.

Table 6 displays the prediction of pseudohomophone and orthographic priming by the rapid temporal ability measures. Rapid temporal processing did not explain significant variance in priming in the adults with reading impairment after partialling for age and IQ. In contrast for the children with reading impairment in Experiment 1, rapid auditory processing may have explained unique variance in pseudohomophone priming because IQ did not account for much variance in the hierarchical regression equation.

In contrast to the children with reading impairment, the correlation between rapid visual and rapid auditory ability in adults was not significant, $r(31) = .23, p = .20$. This suggests that the temporal-processing deficits in the children with reading impairment may reflect a common underlying problem, whereas the adults' reading problems may result from a more specific deficit in rapid auditory processing.

TABLE 6
Hierarchical Regression Equations Predicting (Multiple *R*) Pseudohomophone and Orthographic Priming in Experiment 2 for the Adults Who Were Reading Impaired

	Pseudohomophone Priming	*Orthographic Priming*
Age	.23	.12
IQ	.35*	.16
Rapid visual	.37	.17
Rapid auditory	.38	.17
Rapid auditory	.35	.16
Rapid visual	.38	.17

*$p < .05$ for the unique variance explained by that variable when entered into the equation. Age then IQ were entered into the equation. Next, either rapid visual then rapid auditory or rapid auditory then rapid visual were entered into the equation.

GENERAL DISCUSSION

Support for the Differential Development Model

The goal of this study was to test the differential development model of readers with impairment (presented in Figure 1). This required the measurement of rapid visual ability, rapid auditory ability, orthographic processing, and phonological processing in a group of children and adults with reading impairment. The differential development model argues that, in children, rapid visual ability deficits should be associated with orthographic-processing problems and that rapid auditory ability deficits should be associated with phonological-processing problems (Farmer & Klein, 1995). However, the differential development model argues that orthographic-processing deficits are a reading delay condition and should diminish by adulthood. Thus, there should not be a relation between rapid visual ability and orthographic processing in adults. In contrast, the differential development model argues that phonological deficits are associated with incomplete, inaccurate phonological representations and should continue to adulthood (Harm & Seidenberg, 1999). Thus, there should be a strong relation between rapid auditory ability and phonological processing in adults. Indeed, early deficits in rapid auditory ability and phonological-processing skills may even produce deficits with orthographic processing later in development because the orthographic, phonological, and semantic systems are interactively connected (Plaut & Booth, 1999; Plaut et al., 1996). The snowballing effect of early deficits on later reading development in other areas has been referred to as the Matthew Effect (Stanovich, 1986). Thus, there should also be a relation between rapid auditory ability and orthographic-processing skill in adults.

The results of this study were largely consistent with the differential development model. The children with reading impairment in Experiment 1 showed large deficits on both the exception words measure of orthographic processing and the nonwords measure of phonological processing compared to standard words processing. Furthermore, individual differences in representing rapid visual information explained unique variance in orthographic processing, and individual differences in representing rapid auditory information explained unique variance in phonological processing. The adults with reading impairment in Experiment 2 showed relatively small deficits in the exception words measure of orthographic processing but relatively large deficits in the nonwords measure of phonological processing. Furthermore, rapid visual ability did not explain variance in orthographic or phonological processing, even though there was substantial variance on all of these measures. Individual differences in representing rapid auditory information, however, did explain unique variance in phonological as well as orthographic processing.

Extensions of This Study

There are several ways in which the results of this study can be extended. First, our rapid visual and auditory-processing measures may be contaminated by short-term memory demands, so it is difficult to interpret the effects involving perceptual ability to only differences in transient processing. Further studies should examine the relation of individuation tasks in the auditory and visual modalities (McCroskey & Kidder, 1980; Slaghuis & Lovegrove, 1985) with orthographic and phonological processing. Second, this study employed only two measures of orthographic and phonological processing. To test the generality of our findings, further research should examine whether rapid visual processing is related to other orthographic measures (Olson, Kliegl, Davidson, & Foltz, 1985) and whether rapid auditory processing is related to other phonological measures (Wagner et al., 1994). Third, this study only included a limited sample of control children that were given only a subset of the experimental tasks. Although the results of our study produced some provocative findings, further studies should include control populations who are given all the experimental measures so more definite conclusions can be drawn regarding the absolute magnitude of deficits at different ages. Fourth, this study examined children and adults with reading impairment with a wide range of IQ scores. We accounted for this variability by partialling out the effects of IQ from the relevant analyses. In light of the current controversy over absolute- versus discrepant-based definitions of reading impairment (Shaywitz et al., 1992, 1994; Siegel, 1992; Stanovich & Siegel, 1994), future studies should more directly examine the relation of rapid perceptual ability with orthographic and phonological processing in absolute versus discrepant populations.

Implications for Remedial Intervention

The findings of this study have some general, but tentative, implications. We suggest that low word identification skills in children and adults may be associated with a pervasive deficit in phonological and rapid auditory ability. This implies that children and adults with deficits in these areas would benefit from an extensive intervention program involving a combination of auditory discrimination and phonological training (Merzenich et al., 1996; Tallal et al., 1996; Wagner et al., 1994). Because we believe that these processes are inherently interactive, training at one level would not be as successful as training at both the auditory and phonological levels. This study also suggests that lower identification skills in certain children, but not in adults, may be marked by a deficit in orthographic processing that is related to deficits in rapid visual ability. It appears that with increasing reading exposure adults may be able to effectively develop their orthographic-processing skills. This suggests that children with deficits in visual and orthographic processing may benefit from a program designed to dramatically increase their exposure to low-frequency exception words through reading.

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APPENDIX

Mean Percentile Ranks, Standard Scores, and Grade Equivalents for the Standard Words Measure for the Children and Adults With Reading Impairment in Experiments 1 and 2, Respectively

	Children	*Adults*
Percentile rank	6	12
Standard score[a]	63	77
Grade equivalent[b]	4–0	6–10

[a]$M = 100$, $SD = 15$. [b]The first number is the year, and the second number is the month.