Research Article

Motion-Perception Deficits and Reading Impairment

It's the Noise, Not the Motion

Anne J. Sperling,[1] Zhong-Lin Lu,[2] Franklin R. Manis,[2] and Mark S. Seidenberg[3]

[1]Georgetown University Medical Center, [2]University of Southern California, and [3]University of Wisconsin, Madison

ABSTRACT—***We tested the hypothesis that deficits on sensory-processing tasks frequently associated with poor reading and dyslexia are the result of impairments in external-noise exclusion, rather than motion perception or magnocellular processing. We compared the motion-direction discrimination thresholds of adults and children with good or poor reading performance, using coherent-motion displays embedded in external noise. Both adults and children who were poor readers had higher thresholds than their respective peers in the presence of high external noise, but not in the presence of low external noise or when the signal was clearly demarcated. Adults' performance in high external noise correlated with their general reading ability, whereas children's performance correlated with their language and verbal abilities. The results support the hypothesis that noise-exclusion deficits impair reading and language development and suggest that the impact of such deficits on the development of reading skills changes with age.***

Although dyslexia is usually diagnosed by poor reading and phonological impairment, the underlying neurobiological cause remains unclear, and individuals with dyslexia frequently exhibit impairments in other, nonlinguistic areas, including visual processing, motor sequencing, and attention (e.g., Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998; Demb, Boynton, & Heeger, 1998). The variety of observed impairments suggests that reading problems may be only one of several interrelated outcomes of neurological deficits affecting multiple brain systems.

Address correspondence to Anne J. Sperling, Office of Science Policy, Planning, and Communications, National Institute of Mental Health, 6001 Executive Blvd., Bethesda, MD 20892, e-mail: sperlinga@mail.nih.gov.

One proposed cause of dyslexia is a deficit involving the magnocellular visual pathway. Some dyslexic individuals are less sensitive than their nondyslexic peers to luminance patterns and motion displays with high temporal and low spatial frequency (e.g., Eden et al., 1996; Lovegrove, Bowling, Badcock, & Blackwood, 1980), visual features preferentially associated with the magnocellular pathway, yet perform normally on tasks preferentially associated with the parvocellular pathway, such as those involving color and form (Merigan & Maunsell, 1993; Schiller & Malpeli, 1978). A magnocellular impairment could affect reading directly (e.g., by interfering with orthographic processing) or indirectly (e.g., via attention; Lovegrove et al., 1980), or it could be part of a general deficit in temporal processing affecting both vision and audition (Tallal, Miller, & Fitch, 1993). Although the magnocellular hypothesis is attractive for its potential to unify disparate aspects of the dyslexic phenotype, an increasing number of studies have failed to support it (Ramus, 2003).

We (Sperling, Lu, Manis, & Seidenberg, 2005) proposed an alternative theory of dyslexia based on a systems analysis of observers (Lu & Dosher, 1998). Signal enhancement and noise exclusion are different mechanisms by which attention improves perception. Signal enhancement involves maintaining signal integrity during processing. Noise exclusion involves optimizing the perceptual filter so that signal is processed and noise is excluded. We proposed that deficits in noise exclusion, not magnocellular or temporal processing, contribute to the etiology of dyslexia.

This theory predicts that dyslexic individuals will show performance deficits in both magnocellular and parvocellular types of tasks in the presence of high levels of external noise, and in neither type of task at lower levels of external noise. This is exactly what we found in grating detection: Dyslexic children had deficits detecting both gratings with high temporal frequency and low spatial frequency and gratings with low temporal frequency and high spatial frequency when the gratings were embedded in external noise, but critically, showed no deficits with either type of grating when the stimuli were presented without noise (Sperling et al., 2005).

The present study addressed two interrelated considerations raised by our initial findings. First, a strong prediction of the hypothesis is that multiple types of signal processing, not merely the spatial-temporal processing in the initial study, should be affected in dyslexia. Second, although our study evaluated the magnocellular-deficit theory using grating detection, most of the evidence for this theory has derived from studies on motion perception. To address these two concerns, the current study examined the noise-exclusion hypothesis using a motion-perception task. Obtaining the predicted effects in both spatial-temporal and motion experiments would indicate that the effects are due to noise, rather than a magnocellular deficit.

Studies by Demb et al. (1998) and Eden et al. (1996) found that dyslexic individuals had impaired motion perception accompanied by reduced blood-oxygenation-level-dependent responses in area MT+/V5, an area that is essential for motion perception and that receives projections mainly from the magnocellular layers of the lateral geniculate nucleus (Merigan & Maunsell, 1993). Although the results from these studies have been used to support the magnocellular theory, it is unclear whether they reflected deficits in motion perception or external-noise exclusion: In these studies, high noise was present in the form of low luminance and the evaluation of simultaneously or successively presented displays. It is also unclear whether the observed deficit can be wholly attributed to a magnocellular origin because both visual pathways contribute to motion perception (Lu, Lesmes, & Sperling, 1999; Merigan & Maunsell, 1993). More recent evidence supports the idea that dyslexic adults have problems integrating complex motion information, rather than magnocellular deficits (Hill & Raymond, 2002). In addition, the relationships between these deficits and components of reading are ambiguous. Motion-perception thresholds reported in some studies were more highly correlated with measures of orthographic processing skill than with measures of phonological processing skill (Talcott et al., 2000), a finding inconsistent with the predictions of both the magnocellular and the temporal-processing hypotheses. Finally, Hulslander et al. (2004) obtained evidence that the contribution of motion threshold to variance in reading skills becomes nonsignificant when variability in verbal IQ is taken into account.

In summary, the studies just reviewed are consistent with the noise-exclusion hypothesis, insofar as an impaired ability to focus on the motion signal and discard noise, rather than a magnocellular deficit, could have increased motion thresholds for dyslexic individuals. Nevertheless, without a specific examination of the effect of noise level, previous studies do not unequivocally favor either theory. The present study tested a critical prediction of the noise-exclusion theory, that on tasks involving coherent motion, poor readers should perform at the same level as good readers in the absence of external noise, and much worse than good readers in the presence of higher levels of external noise. We tested this prediction with adults and children who were good and poor readers.

EXPERIMENT 1: ADULTS

Method

Fifty-five participants were recruited at the University of Southern California (USC)—47 from undergraduate psychology classes and 8 via advertisements. All recruitment material specified that fluency in English and either normal reading abilities or a history of reading problems were required. Psychology students received course credit in return for their participation; other participants received payment. Informed consent was obtained.

Reading ability was evaluated with the Word Identification and Word Attack tests of the Woodcock-Johnson Tests of Achievement–III (Mather & Woodcock, 2001a). Cognitive processing was evaluated with the Spatial Relations and Verbal Comprehension composite tests of the Woodcock-Johnson Tests of Cognitive Abilities–III (Mather & Woodcock, 2001b). We administered additional word-reading tests: Exception Word Reading, which involves reading 70 items increasing in orthographic complexity and decreasing in frequency (e.g., eye . . . silhouette) and has a presentation format similar to that of Word Identification (6 words per test page), and Orthographic Choice, which requires participants to decide which of two printed stimuli, a word or a pseudohomophone (e.g., *rain* vs. *rane*) is a correctly spelled word (60 trials).

To be included in the poor-reader group, participants had to score below the 25th percentile on Word Attack and no less than 1 standard deviation below the national mean (i.e., a standard score of at least 85) on Spatial Relations and Verbal Comprehension. Inclusion in the good-reader group required scoring above the 40th percentile on both Word Identification and Word Attack and having a standard score of at least 85 on both cognitive-ability tests. Twenty-seven participants qualified for the poor-reader group (5 male, 22 female); 19 had histories of reading difficulties, and 8 did not. Twenty-eight participants qualified for the good-reader group (8 male, 20 female); 1 reported being a slow reader.

The motion tasks were run on a Macintosh G4 with a 10-bits/channel Radius Thundercolor graphics card and an Apple Multiple Scan 720 monitor (refresh rate: 75 Hz; resolution: 640 × 480). The tasks were programmed using Matlab 5.2 with Psychophysics Toolbox (Brainard, 1997). Room lights were extinguished, and participants were given the opportunity to adapt.

All versions of the experiment followed the same procedures. Background and dot luminance were set at 12.7 cd/m^2 and 18.3 cd/m^2, respectively. A 6.5° × 6.5° random-dot-kinetics display comprising 300 dots (0.015° × 0.015°) was viewed from a distance of 72 cm. A fixation cross appeared in the center of the screen 500 ms prior to the motion display and remained on the screen throughout the trial. Apparent motion was created by randomly selecting a fraction of the dots and replotting them 0.06° in a single direction (left or right) after a 67-ms delay. The remaining dots were replotted randomly. Each signal or noise dot had a lifetime of only 2 frames, to prevent tracking. A total of 15 frames generated an apparent velocity of 0.90°/s, for approximately 1,000 ms. Participants indicated motion direction by pressing buttons on the keyboard. Auditory feedback signaled correct responses.

There were three versions of the experiment. Prior to each version, participants practiced with 40 suprathreshold stimuli (eight levels of coherence, 5 trials each) and had the opportunity to repeat the practice if they or the experimenter felt more practice was warranted. Version 1 involved motion in high external noise. Signal and noise dots were the same light gray in luminance (and color) and were presented against the darker gray background. Eight randomly intermixed coherence levels were used. The levels ranged from 0.3% to 25%, in log steps, and there were 30 trials at each level, for a total of 240 trials. In Version 2, signal dots were red (same luminance as before), which increased signal salience; therefore, participants could more easily focus on the signal and ignore the noise dots. Pilot studies indicated that the addition of chromatic cues dramatically lowers thresholds (Croner & Albright, 1997). Therefore, the eight coherence levels in Version 2 ranged from 0.1% to 15%. In Version 3, only coherent red dots were used (no noise dots); there were eight signal levels, ranging from 0.1% to 15%. We labeled the signal levels in Version 3 as though the noise dots were present. Thus, Versions 2 and 3 involved the same number of signal dots in corresponding conditions, but Version 3 did not contain noise dots. Version 3 had the lowest possible noise level, yet ample motion noise was present because each dot still appeared for only 2 out of the 15 total frames. The order of the versions was counterbalanced across participants.

TABLE 1

Mean Reading and Cognitive Scores of the Adults in Experiment 1

Test	Good readers (n = 28)	Poor readers (n = 27)	p_{rep}	d
WJ-III Tests of Achievement				
Word Identification	108 (7.5)	94 (6.4)	>.99	2.01
Word Attack	103 (6.2)	84 (4.3)	>.99	3.55
WJ-III Tests of Cognitive Abilities				
Verbal Comprehension	104 (9.5)	97 (7.5)	>.97	0.82
Spatial Relations	109 (10.6)	102 (8.8)	>.97	0.72
Orthographic Choice (d')	3.4 (0.4)	2.8 (0.4)	>.97	1.5
Exception Word Reading (out of 70)	63 (2.7)	57 (3.4)	>.99	1.96

Note. All scores are standardized unless noted. Standard deviations are in parentheses. The mean age of the good readers was 21 years, 5 months (SD = 3 years, 2 months), and the mean age of the poor readers was 20 years, 8 months (SD = 1 year, 6 months); the difference was not significant. WJ-III = Woodcock-Johnson III (Mather & Woodcock, 2001a, 2001b).

Results and Discussion

Table 1 presents the participants' scores on the reading and cognitive tests. Exception Word scores are the mean number of correctly pronounced words out of 70. Scores on the forced-choice Orthographic Choice test were converted to d' values. Poor readers had significantly lower scores than good readers in word identification, phonological decoding, and orthographic skill.

Although all participants met the criteria for verbal and visual-spatial ability, poor readers had significantly lower scores than good readers on the Verbal Comprehension and Spatial Relations tests ($p_{rep} > .97$, $p < .01$).[1] The difference in Verbal Comprehension was not surprising, as the degree to which verbal ability can be considered independent of reading experience is questionable (Stanovich, 1986). Although there was a group difference in Spatial Relations scores, the mean of the poor-reader group was higher than the mean for the national-norm group.

Performance on the three versions of the motion experiment was assessed using Weibull functions (Weibull, 1951) to fit the psychometric functions:

$$Pc = 0.50 + (\max - 0.50) \times (1 - 2^{-(c/\alpha)^{\eta}}),$$

where Pc = proportion correct, max = maximum performance (allowed to vary between 90% and 100%), c = coherence level, α = threshold at (max/2 + 0.25), and η = slope of the psychometric function. The psychometric curves were used to derive the coherence level at which a participant could respond correctly at a 75% criterion level. Setting the criterion level at 75% guaranteed that performance was assessed well below ceiling. The tasks were challenging and tiring; several participants were unable to perform at criterion level, despite having performed well in practice (the numbers were similar across groups and versions). Criterion levels could not be accurately estimated by extrapolation. Therefore, only data from those participants who reached the 75% criterion by at least the highest level of coherence were analyzed. Twenty-two poor readers and 22 good readers met the criterion on Version 1; 20 poor readers and 27 good readers met the criterion on Version 2; and 22 poor readers and 24 good readers met the criterion on Version 3.

Figure 1 displays the distribution of thresholds on the three versions of the task. On Version 1 (high noise), poor readers required 3% more coherence on average to reach criterion than good readers did (threshold = 11.7% for poor readers and 8.8% for good readers), $t(37) = 2.3$, $p_{rep} > .94$, $p < .03$, $d = 0.70$. There was no significant difference in performance for either Version 2 or Version 3, which suggests poor readers performed the motion task at a level comparable to that of good readers

[1]Two-tailed p values were converted to p_{rep}: $p_{rep} \approx [1 + (p/(1-p))^{2/3}]^{-1}$ (Killeen, 2005). For several analyses, p values are provided for comparison.

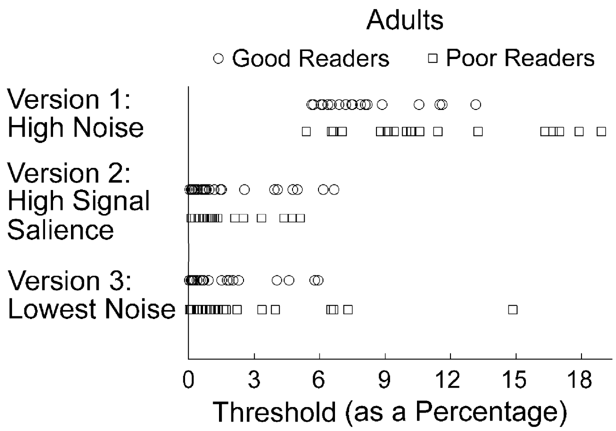

Fig. 1. Distribution of the coherence threshold at the 75%-correct criterion for good and poor readers in Experiment 1 (adults). Results are shown separately for Version 1 (high noise), Version 2 (high signal salience), and Version 3 (no noise dots—lowest level of external noise).

under these conditions (Version 2: threshold = 2.0% for poor readers and 1.6% for good readers, $p_{rep} < .68$; Version 3: threshold = 1.7% for poor readers and 1.5% for good readers, $p_{rep} < .57$). Performance did not differ between Versions 2 and 3, paired-samples t tests, $t(42) = 0.51$, $p_{rep} < .65$. Coloring the signal dots red may have increased the signal salience so much in Version 2 that the noise dots had little effect.

Hierarchical regression analyses were conducted both with the entire sample and within individual groups to determine which reading skills were related to task performance. Scores more than 1.5 standard deviations from the individual group mean were trimmed from analyses. In Version 1, threshold accounted for 9% of the variance in Word Attack scores, independently of both cognitive measures, $t = -2.48$, $p_{rep} > .92$, $p < .05$, and 11.3% of the variance in Orthographic Choice scores, independently of Spatial Relations scores, $t = -2.12$, $p_{rep} > .92$ (Verbal Comprehension scores were not correlated with Orthographic Choice scores). No other samplewide or within-groups correlations, including correlations with cognitive measures, were significant for Version 1. Threshold on Version 2 was not correlated with any reading or cognitive test scores, either across or within groups. Threshold on Version 3 was significantly correlated with Verbal Comprehension scores across the sample, $r(46) = -.32$, $p_{rep} > .92$, although the distribution of thresholds was highly skewed. No correlations were significant within individual groups.

EXPERIMENT 2: CHILDREN

Method

Seventy-five children ages 9 through 14 participated. Poor readers were recruited through two local schools for children with learning disabilities (Summit View Schools) and tested in an unused classroom there. Potential good readers and additional poor readers were recruited from local public and private schools and advertisements. These children were tested in a USC lab. Parental permission and each child's assent were obtained prior to testing. Children received money, small prizes, or gift certificates as compensation. Parents completed the Disruptive Behavior Rating Scale (Barkley & Murphy, 1998) as a screen for attention-deficit and conduct disorders.

Reading ability was evaluated with the Word Identification and Word Attack subtests of the Woodcock Reading Mastery Tests, Revised, Form G (Woodcock, 1987); the Formal Reading Inventory (Weiderholt, 1986); and the Test of Word Reading Efficiency (Torgesen, Wagner, & Rashotte, 1999). Phonological awareness was evaluated with the Elision test of the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999). Orthographic skill was measured with child versions of the Exception Word Reading and Orthographic Choice tests.

Oral language was evaluated with the Receptive One-Word Picture Vocabulary Test (Brownell, 2000) and two tests selected from the Clinical Evaluation of Language Fundamentals, Recalling Sentences and Concepts and Directions (Semel, Wiig, & Secord, 1995).

Cognitive ability was estimated with Verbal and Performance Scale subtests of the Wechsler Intelligence Scales for Children–III (WISC–III; Wechsler, 1991): Vocabulary and Similarities scores provided the Verbal IQ estimate, and Block Design and Picture Completion scores provided the Performance IQ estimate. To be included in the poor-reader group, children needed to have Word Identification or Word Attack scores at or below the 25th percentile; children in the good-reader group needed to score at or above the 40th percentile on both of these tests. All children were required to have a Performance IQ estimate of at least 7. Thirty-two children qualified as poor readers (20 male, 12 female), and 27 qualified as good readers (9 male, 18 female). The remainder of the children ($n = 16$) had reading scores falling between the cutoffs or did not meet the IQ criterion.

The methods were similar to those in Experiment 1, with a few modifications. Two Macintosh G4 computers were used. The first was the one from Experiment 1, this time paired with a 19-in. View Sonic P95*f* monitor; the second had a native 10-bit graphics card and was paired with a 19-in. View Sonic P95*f*+ monitor. Monitor refresh rate and screen resolution were the same as in Experiment 1. The children were given the opportunity to adapt to the dim conditions while performing an auditory language task.

The motion paradigms were modified in order to make them more suitable for children. The background luminance was raised to 13.7 cd/m^2, and the luminance of the dots (both gray and red) was set at 20.1 cd/m^2. Version 3 was eliminated because we did not find any significant difference between Versions 2 and 3 in Experiment 1 and a shorter experiment was desirable. The coherence range was increased to 2 to 30% in Version 1, and narrowed to 0.2 to 10% in Version 2. The children were given 24 suprathreshold practice trials prior to each version (eight levels, 3 trials each). There were 160 randomly intermixed test trials in

TABLE 2
Mean Reading and Cognitive Scores of the Children in Experiment 2

Test	Good readers (n = 27)	Poor readers (n = 32)	p_{rep}	d
WRMT–R				
Word Identification	108 (8.0)	79 (7.4)	>.99	3.78
Word Attack	108 (8.0)	86 (8.9)	>.99	2.59
CTOPP: Elision	11.4 (2.1)	7.1 (2.8)	>.99	1.79
TOWRE[a]: Sight Word Reading	109 (9.5)	80 (9.1)	>.99	3.13
FRI: Silent Reading Quotient	118 (15)	89 (16)	>.99	1.86
ROWPVT: standard score	110 (17)	96 (11)	>.99	0.99
CELF-3				
Recalling Sentences	11.6 (2.2)	6.9 (3.4)	>.99	1.62
Concepts and Directions	11.8 (2.9)	7.6 (3.2)	>.99	1.35
Orthographic tasks				
Exception Word Reading (out of 70)	61 (4.9)	37 (11)	>.99	2.74
Orthographic Choice (d')	2.86 (0.89)	1.31 (0.59)	>.99	2.09
Latency (s)	1.05 (0.25)	2.04 (0.99)	>.99	1.32
WISC–III				
Vocabulary	12.1 (2.6)	8.4 (3.0)	>.99	1.31
Similarities	12.4 (2.3)	9.4 (2.8)	>.99	1.16
Block Design	11.5 (3.2)	10.6 (3.1)	n.s.	0.29
Picture Completion	12.0 (2.6)	10.5 (2.6)	>.92	0.58

Note. All scores are standardized or scaled unless noted. Standard deviations are in parentheses. The mean age of the good readers was 11 years, 2 months (SD = 1 year, 4 months; range: 9 years, 4 months to 13 years, 8 months); the mean age of the poor readers was 12 years, 2 months (SD = 1 year, 4 months; range: 9 years, 1 month to 14 years, 0 months); the difference was significant, $p_{rep} > .97$, $d = 0.75$. CELF-3 = Clinical Evaluation of Language Fundamentals (Semel, Wiig, & Secord, 1995); CTOPP = Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999); FRI = Formal Reading Inventory (Weiderholt, 1986); ROWPVT = Receptive One-Word Picture Vocabulary Test (Brownell, 2000); TOWRE = Test of Word Reading Efficiency (Torgesen, Wagner, & Rashotte, 1999); WISC–III = Wechsler Intelligence Scales for Children–III (Wechsler, 1991); WRMT–R = Woodcock Reading Mastery Tests, Revised (Woodcock, 1987).
[a]These scores are averages of scores on Forms A and B.

each version (eight levels, 20 trials each). Participants spoke their responses aloud to the experimenter, who then pressed the appropriate response keys. All children performed Version 2 first because there was no a priori intention to compare within-subjects performance on Version 1 and Version 2. Whenever possible, children who did not achieve at least 80% correct performance at the highest level of coherence on either version were retested on that version in a later testing session.

Results and Discussion

Table 2 presents the children's reading and cognitive scores. Good readers were younger than poor readers by approximately 12 months, a difference that was significant ($p_{rep} > .97$). Orthographic Choice scores reflect d' values.

Poor readers had significantly lower standard scores than good readers on all tests of word reading, passage comprehension, phonological processing, orthographic skill, and receptive and

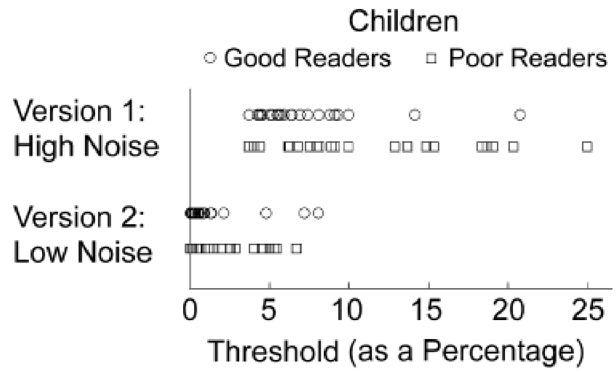

Fig. 2. Distribution of the coherence threshold at the 75%-correct criterion for good and poor readers in Experiment 2 (children). Results are shown separately for Version 1 (high noise) and Version 2 (low noise, high signal).

expressive language. They also had lower scores on both Verbal tests from the WISC–III. Their Performance test scores were mixed; there were no group differences on Block Design, but poor readers had lower scores on Picture Completion than good readers did. In the poor-reader group, 1 child scored within the clinical range for hyperactivity-impulsivity, and 4 scored within the clinical range for inattention.[2]

Figure 2 illustrates the threshold distributions. The children's data were analyzed in the same manner as the adults'. Several children were unable to reach criterion, particularly on Version 1. Only data from children who successfully reached criterion on both versions were used in the analyses (poor readers: $n = 21$; good readers: $n = 23$). On Version 1, the poor readers had significantly higher thresholds than the good readers (poor readers: 11.5%; good readers: 7.23%), $t(42) = -2.8$, $p_{rep} > .97$, $d = 0.85$. The group difference remained significant after IQ estimates and age were covaried out, $F(4, 37) = 5.0$, $p_{rep} > .92$, $\eta^2 = .12$. There was no significant group difference for Version 2 (threshold = 2.46% for poor readers and 1.44% for good readers), $t(42) = -1.6$, $p_{rep} = .86$, $d = 0.47$.

For correlation and regression analyses, the data were trimmed in the same manner as before. Threshold in Version 1 was marginally correlated with Concepts and Directions scores in poor readers, $r(20) = -.40$, $p_{rep} = .89$, $p = .08$, but not with any measures in good readers. Across the entire sample, when Verbal IQ estimate was partialed out, threshold in Version 1 uniquely accounted for 5% of the variance in another language measure, Recalling Sentences, $t(40) = -2.46$, $p_{rep} > .92$, as well as for 8% of the variance in Elision scores, $t(40) = -2.11$, $p_{rep} > .92$.

Threshold in Version 2 correlated significantly with Orthographic Choice scores within the good-reader group, $r(21) = -.45$, $p_{rep} > .92$. Across the entire sample, even with Verbal IQ estimates, Word Attack scores, and Elision scores partialed out of the regression analysis, threshold in Version 2 accounted for

[2]Exclusion of these children from analyses did not affect the significance of group differences on Versions 1 and 2.

variance in both Word Identification scores (2.5%), $t(39) = -2.37$, $p_{rep} > .92$, and Orthographic Choice scores (10.4%), $t(39) = -2.76$, $p_{rep} > .97$. Thus, threshold in the low-noise version was loosely linked to orthographic ability, independently of phonological processing. There were no significant correlations within the poor-reader group for Version 2.

When thresholds in Version 2 were entered first in the regression (whole sample), high-noise motion accounted for unique variance in Word Identification scores, $F(1, 36) = 4.3$, $p_{rep} > .92$; Elision scores, $F(1, 36) = 5.6$, $p_{rep} > .92$; Recalling Sentences scores, $F(1, 36) = 7.7$, $p_{rep} > .97$; and Concepts and Directions scores, $F(1, 36) = 4.7$, $p_{rep} > .92$. Threshold in the high-noise motion task thus appears to be related to aspects of both reading and oral language. When thresholds in Version 1 were entered first, thresholds in Version 2 accounted for unique variance in Orthographic Choice scores, as well as Word Identification scores, $F(1, 36) = 5.6$, $p_{rep} > .92$, and Word Attack scores, $F(1, 34) = 4.5$, $p_{rep} > .92$.

GENERAL DISCUSSION

We evaluated how noise level affected the motion thresholds of adults and children with and without reading problems. The poor readers' higher threshold in the high-noise condition, compared with their normal performance in the low- and minimal-noise conditions, suggests deficits in noise exclusion and in integrating perceptual information in successive frames, rather than in motion perception per se. In adults, threshold in high noise was related (independently of verbal and visual-spatial ability) to measures of both phonological decoding and orthographic skill, as gauged by the Word Attack and Orthographic Choice tests, respectively. The fact that both orthographic and phonological processing were affected suggests that threshold in adults is related to general reading ability, rather than to a single component skill. The conclusion that the correlations between threshold in Version 1 and the reading measures reflect a connection between reading and noise exclusion, rather than motion perception, is further supported by the absence of a relationship between thresholds in Versions 2 and 3 and the reading and cognitive measures.

Among the children, although the difference in threshold between good and poor readers was partially independent of Verbal IQ, the correlation and regression analyses revealed that threshold had stronger relationships with language measures than with reading measures. The results are consistent overall with our previous findings that in children, contrast thresholds under noisy conditions are associated with both reading and oral language skills (Sperling et al., 2005; see also Hulslander et al., 2004).

We also found a surprisingly robust link between threshold in the low-noise version and orthographic skill, particularly among the nondyslexic children. Although we might have expected some relationship between orthographic skill and threshold in the high-noise version given previous findings (e.g., Cornelissen et al., 1998; Talcott et al., 2000), the strength of the correlation in the low-noise version exceeded expectations. This result is reconciled with the previous findings if differences in methodology are taken into account. The earlier studies used displays with higher contrast than our high-noise versions, and signal dots persisted for four frames. Thus, their conditions were closer to those of our low-noise version, which yielded similar results.

In summary, the results of these experiments are consistent with the theory that adults and children with reading problems have difficulty excluding noise (Sperling et al., 2005). Similar findings have been obtained using auditory stimuli: For example, in studies by Brady, Shankweiler, and Vann (1983) and Ziegler, Pech-Georgel, George, Alario, and Lorenzi (2005), dyslexic children exhibited deficits in speech perception when speech signals were presented with white or masking noise, but not when they were presented in the clear. We (Sperling, Lu, & Manis, 2004) found that perceptual integration difficulties of poor readers extended to a categorical learning task. Poor readers had difficulty with a task that required them to identify relevant features and ignore irrelevant or inconsistent features in a complex geometric display. However, when perceptual integration and inconsistency were minimized in the explicit version of the task, they performed like good readers. Together, these studies yield a consistent picture: Compared with good readers, poor readers had higher coherence and contrast thresholds under high-noise conditions, and learned more slowly and less accurately when learning involved multiple feature dimensions. When noise level was reduced, these differences were eliminated.

The present studies also yielded evidence about the longer-term developmental consequences of the hypothesized deficit. In children, thresholds were mainly correlated with language and verbal ability, which are important in early reading development. In adults, thresholds were more specifically related to reading ability. This suggests a developmental trajectory whereby the early effects of noise-exclusion deficits on general verbal abilities eventually resolve, leaving residual effects on reading. This conclusion is consistent with studies by Bruck (1990) and Wright and Zecker (2004) indicating that deficits related to different components of language and reading change and sometimes resolve at different points in development.

The future challenge is to understand the neurobiological basis of the noise-exclusion deficit. Deficits in noise exclusion implicate nonoptimal tuning of neurons, which has been shown to result from abnormal cortical gamma-aminobutyric acid (GABA) activity (Winterer & Weinberger, 2004). We speculate that the observed deficit in noise exclusion in poor readers may reflect some impairment in the interactions of the GABA neurotransmitter system.

Acknowledgments—This work was supported by National Institute of Child Health and Human Development Grant

HD29891 (Frank Manis, principal investigator). This article was written while Anne Sperling was a postdoctoral fellow at Georgetown University Medical Center. No official support or endorsement by the National Institute of Mental Health is intended or should be inferred.

REFERENCES

Barkley, R.A., & Murphy, K.R. (1998). *Attention-Deficit Hyperactivity Disorder: A clinical workbook* (2nd ed.). New York: Guilford Press.

Brady, S., Shankweiler, D., & Vann, S. (1983). Speech perception and memory coding in relation to reading ability. *Journal of Experimental Child Psychology*, *35*, 345–367.

Brainard, D.H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436.

Brownell, R. (Ed.). (2000). *Receptive One-Word Picture Vocabulary Test: Manual* (2nd ed.). Novato, CA: Academic Therapy Publications.

Bruck, M. (1990). Word-recognition skills of adults with childhood diagnoses of dyslexia. *Developmental Psychology*, *26*, 439–454.

Cornelissen, P.L., Hansen, P.C., Hutton, J., Evangelinou, V., & Stein, J. (1998). Magnocellular visual function and children's single word reading. *Vision Research*, *38*, 471–482.

Croner, L.J., & Albright, T.D. (1997). Image segmentation enhances discrimination of motion in visual noise. *Vision Research*, *37*, 1415–1427.

Demb, J.B., Boynton, G.M., & Heeger, D.J. (1998). Functional magnetic resonance imaging of early visual pathways in dyslexia. *Journal of Neuroscience*, *18*, 6939–6951.

Eden, G.F., Vanmeter, J., Rumsey, J., Maisog, J., Woods, R., & Zeffiro, T. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature*, *382*, 66–69.

Hill, G.T., & Raymond, J.E. (2002). Deficits in motion transparency in adult developmental dyslexics with normal unidirectional motion sensitivity. *Vision Research*, *42*, 1195–1203.

Hulslander, J., Talcott, J., Witton, C., DeFries, J., Pennington, B., Wadsworth, S., Willcutt, E., & Olson, R. (2004). Sensory processing, reading, IQ and attention. *Journal of Experimental Child Psychology*, *88*, 274–295.

Killeen, P.R. (2005). An alternative to null-hypothesis significance tests. *Psychological Science*, *16*, 345–353.

Lovegrove, W.J., Bowling, A., Badcock, D., & Blackwood, M. (1980). Specific reading disability: Differences in contrast sensitivity as a function of spatial frequency. *Science*, *210*, 439–440.

Lu, Z.-L., & Dosher, B.A. (1998). External noise distinguishes attention mechanisms. *Vision Research*, *38*, 1183–1198.

Lu, Z.-L., Lesmes, L.A., & Sperling, G. (1999). The mechanism of isoluminant chromatic motion perception. *Proceedings of the National Academy of Sciences, USA*, *96*, 8289–8294.

Mather, N., & Woodcock, R.W. (2001a). *Examiner's manual: Woodcock-Johnson III Tests of Achievement*. Itasca, IL: Riverside Publishing.

Mather, N., & Woodcock, R.W. (2001b). *Examiner's manual: Woodcock-Johnson III Tests of Cognitive Abilities*. Itasca, IL: Riverside Publishing.

Merigan, W.H., & Maunsell, J.H.R. (1993). How parallel are the primate visual pathways? *Annual Review of Neuroscience*, *16*, 369–402.

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

Schiller, P.H., & Malpeli, J.G. (1978). Function specialization of the lateral geniculate nucleus laminae of the rhesus monkey. *Journal of Neurophysiology*, *41*, 788–797.

Semel, E., Wiig, E.H., & Secord, W.A. (1995). *Examiner's manual: CELF®* (3rd ed.). San Antonio, TX: The Psychological Corp.

Sperling, A.J., Lu, Z.-L., & Manis, F.R. (2004). Slower implicit categorical learning in adult poor readers. *Annals of Dyslexia*, *54*, 281–303.

Sperling, A.J., Lu, Z.-L., Manis, F.R., & Seidenberg, M.S. (2005). Deficits in perceptual noise exclusion in developmental dyslexia. *Nature Neuroscience*, *9*, 862–863.

Stanovich, K.E. (1986). Matthew effects in reading: Some consequences of individual differences in the acquisition of literacy. *Reading Research Quarterly*, *21*, 360–407.

Talcott, J.B., Witton, C., McLean, M.F., Hansen, P.C., Rees, A., Green, G.G., & Stein, J.F. (2000). Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences, USA*, *97*, 2952–2957.

Tallal, P., Miller, S., & Fitch, R.H. (1993). Neurobiological basis of speech: A case for the preeminence of temporal processing. In C. von Euler, R.R. Llins, A.M. Galaburda, & P. Tallal (Eds.), *Temporal information processing in the central nervous system: Special reference to dyslexia and dysphasia* (Annals of the New York Academy of Sciences Vol. 682, pp. 27–47). New York: New York Academy of Sciences.

Torgesen, J.K., Wagner, R.K., & Rashotte, C.A. (1999). *Examiner's manual: Test of Word Reading Efficiency*. Austin, TX: Pro-Ed.

Wagner, R.K., Torgesen, J.K., & Rashotte, C.A. (1999). *Examiner's manual: Comprehensive Test of Phonological Processing*. Austin, TX: Pro-Ed.

Wechsler, D. (1991). *Wechsler Intelligence Scales for Children–III™*. San Antonio, TX: The Psychological Corp.

Weibull, W. (1951). Statistical distribution function of wide applicability. *Journal of Applied Mechanics*, *18*, 292–297.

Weiderholt, J.L. (1986). *Formal Reading Inventory*. Austin, TX: Pro-Ed.

Winterer, G., & Weinberger, D.R. (2004). Genes, dopamine, and cortical signal-to-noise ratio in schizophrenia. *Trends in Neurosciences*, *27*, 683–690.

Woodcock, R.W. (1987). *Woodcock Reading Mastery Tests–Revised*. Circle Pines, MN: American Guidance Services.

Wright, B.A., & Zecker, S.G. (2004). Learning problems, delayed development, and puberty. *Proceedings of the National Academy of Sciences, USA*, *101*, 9942–9946.

Ziegler, J.C., Pech-Georgel, C., George, F., Alario, F.-X., & Lorenzi, C. (2005). Deficits in speech perception predict language learning impairment. *Proceedings of the National Academy of Sciences, USA*, *102*, 14110–14115.

(RECEIVED 9/8/05; REVISION ACCEPTED 12/20/05; FINAL MATERIALS RECEIVED 1/10/06)