

# Two Visual Motion Processing Deficits in Developmental Dyslexia Associated with Different Reading Skills Deficits

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## Abstract

■ Developmental dyslexia is associated with deficits in the processing of visual motion stimuli, and some evidence suggests that these motion processing deficits are related to various reading subskills deficits. However, little is known about the mechanisms underlying such associations. This study lays a richer groundwork for exploration of such mechanisms by more comprehensively and rigorously characterizing the relationship between motion processing deficits and reading subskills deficits. Thirty-six adult participants, 19 of whom had a history of developmental dyslexia, completed a battery of visual, cognitive, and reading tests. This battery combined motion processing and reading subskills measures used across previous studies and added carefully matched visual processing control tasks. Results suggest that there are in fact two distinct motion processing deficits in developmental dyslexia, rather than one as assumed by previous research, and that each of

these deficits is associated with a different type of reading subskills deficit. A deficit in detecting coherent motion is selectively associated with low accuracy on reading subskills tests, and a deficit in discriminating velocities is selectively associated with slow performance on these same tests. In addition, evidence from visual processing control tasks as well as self-reports of ADHD symptoms suggests that these motion processing deficits are specific to the domain of visual motion, and result neither from a broader visual deficit, nor from the sort of generalized attention deficit commonly comorbid with developmental dyslexia. Finally, dissociation between these two motion processing deficits suggests that they may have distinct neural and functional underpinnings. The two distinct patterns of motion processing and reading deficits demonstrated by this study may reflect separable underlying neurocognitive mechanisms of developmental dyslexia. ■

## INTRODUCTION

Developmental dyslexia (hereafter, dyslexia) is a specific reading disability that has been estimated to affect 5–10% of the population (Shaywitz, 1998). It is generally diagnosed when low reading achievement accompanies normal intelligence, adequate education, and lack of other (e.g., psychological) salient explanatory factors (American Psychiatric Association, 2000). Dyslexia is associated with a broad range of abnormalities that extend beyond reading per se, including those of visual and auditory processing (Talcott & Witton, 2002; Stein, 2001; Wright, Bowen, & Zecker, 2000), genetics (Fisher & DeFries, 2002), neurological structure and function (Habib, 2000), motor coordination (Nicolson, Fawcett, & Dean, 2001), phonological awareness (Ramus, 2001), and naming speed (Wolf & Bowers, 1999).

This study focuses on the domain of visual processing in dyslexia. The most consistent evidence for a basic visual processing deficit among dyslexic persons is their relatively poor performance on tests of motion processing. Deficits have been found on both of the most commonly studied indices of motion processing: coherent motion detection (Hansen, Stein, Orde, Winter, & Talcott, 2001; Ridder, Borsting, & Banton, 2001; Everatt,

Bradshaw, & Hibbard, 1999; Slaghuis & Ryan, 1999; Raymond & Sorenson, 1998; Talcott et al., 1998; Talcott, Hansen, Assoku, & Stein, 2000; Witton et al., 1998; Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; though see also Kronbichler, Hutzler, & Wimmer, 2002) and velocity discrimination (Demb, Boynton, Best, & Heeger, 1998; Ramus et al., 2003). Several other findings also lend converging support to the idea of a basic motion processing deficit in dyslexia. First, a well-known study that examined dyslexic brains postmortem found abnormal cell structure and density in the lateral geniculate nucleus (LGN), a neural structure essential for the processing of visual motion (Livingstone, Rosen, Drislane, & Galaburda, 1991). Second, functional magnetic resonance imaging (fMRI) (Demb, Boynton, & Heeger, 1997; Demb, Boynton, & Heeger, 1998; Eden et al., 1996, though see also Vanni, Uusitalo, Kiesila, & Hari, 1997) and electrophysiological (Kuba, Szanyi, Gayer, Kremlacek, & Kubova, 2001; Kubova, Kuba, Peregrin, & Novakova, 1996; Livingstone et al., 1991) studies have provided evidence for anomalous neural activation in visual motion processing brain area MT+/V5 to motion stimuli. Finally, a recent fMRI study has demonstrated abnormal neural activation to word stimuli in an area corresponding roughly to MT+/V5 (Shaywitz et al., 2002). Thus, there exists evidence from multiple

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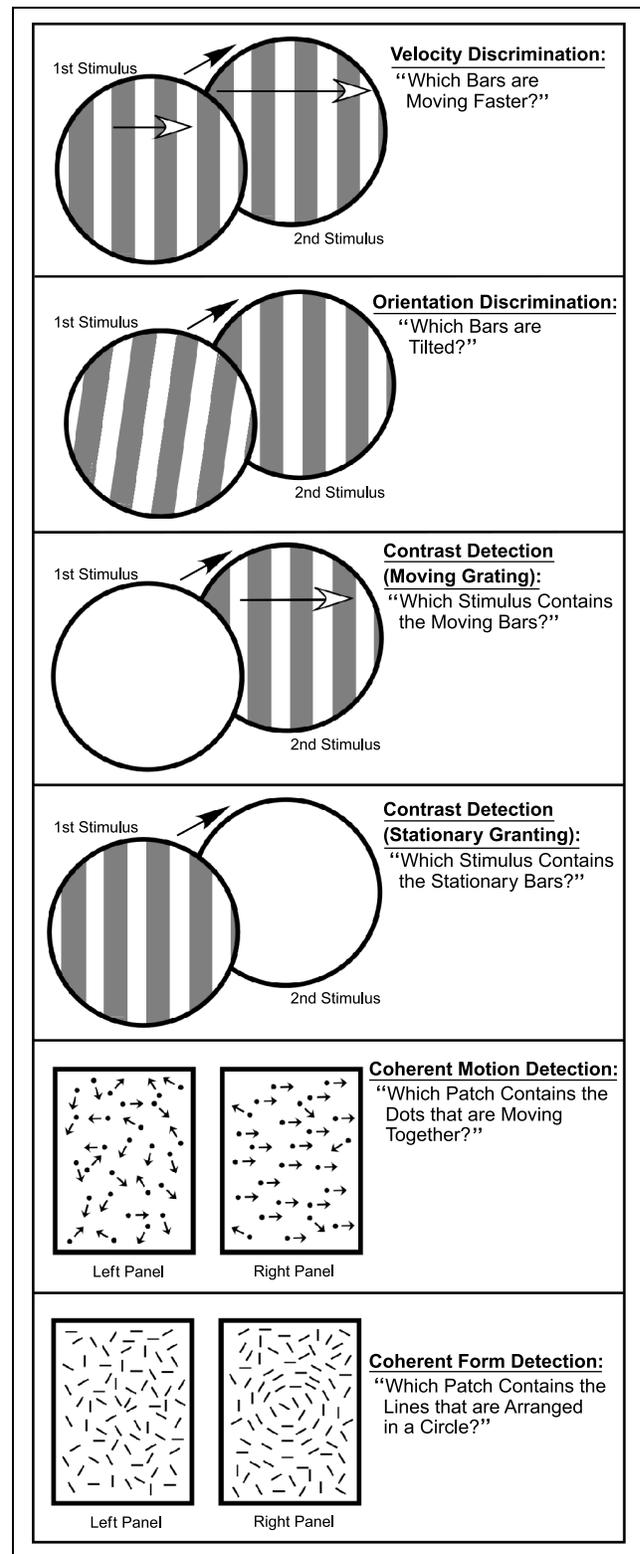
domains suggesting abnormality of visual motion processing and underlying neural structure and function in dyslexia.

Our study is the first to test both coherent motion detection and velocity discrimination (see Figure 1) in the same groups of dyslexic and nondyslexic participants, and also uses a wider range of reading subskills measures than did previous studies of motion processing in dyslexia.

It thus presents a unique opportunity to more comprehensively examine associations between motion processing deficits and reading subskills deficits. The following studies have examined such associations using one of these two motion tasks and one or a subset of the types of reading tasks used in this study: Two studies (Talcott et al., 1998; Witton et al., 1998) found positive associations between coherent motion detection and accuracy (and in the latter case speed) of phonological decoding among dyslexic and nondyslexic adults. Demb, Boynton, Best, et al. (1998) found that dyslexic and nondyslexic adults who performed better at velocity discrimination also tended to read faster. Cornelissen, Hansen, Gilchrist, et al. (1998) and Cornelissen, Hansen, Hutton, Evangelinou, and Stein (1998) found positive associations in unselected samples of children between coherent motion detection and the ability to accurately localize and decode letters, a component aspect of orthographic skill. Talcott, Witton, et al. (2000) showed that coherent motion detection was associated with accuracy of orthographic recognition above and beyond its association with accuracy of phonological decoding in another unselected sample of children. Finally, Talcott et al. (2002) showed in a large unselected sample of 350 primary school children that coherent motion detection was related to both orthographic recognition accuracy and phonological decoding accuracy, even after controlling for general cognitive skills.

The wider breadth of motion processing and reading subskills tests administered to the same participants in the current study allows us to extend these previous findings in two important ways. First, we are able to provide evidence that there are in fact two distinct motion processing deficits in dyslexia, rather than one as assumed by previous research. Second, we are able to show that poorer detection of coherent motion is selectively associated with less accurate performance on reading subskills tests, while poorer discrimination of velocities is selectively associated with slower performance on these same tests.

When trying to isolate a basic sensory deficit, it is important to include sensory control tasks in order to rule out alternative explanations for deficits found on the main tasks of interest. Perhaps most importantly for the current study, given the high association between dyslexia and attention deficit hyperactivity disorder (ADHD), we were interested in establishing whether motion processing deficit was associated with dyslexia per se, or whether



**Figure 1.** Schematic illustrations of visual processing tasks: velocity discrimination task and three control tasks (orientation discrimination, moving contrast detection, and static contrast detection), plus coherent motion detection task and its control task (coherent form detection). Note that illustrations are not necessarily drawn to scale, and that actual stimuli did not include distinct borders.

it was associated as well with an attention deficit. In addition, we were interested in establishing whether visual motion processing deficits in dyslexia were specific to the domain of motion, or whether they were the result of a broader visual deficit. The present study finds motion processing deficits in our dyslexic participants even after controlling for performance on visual processing control tasks, suggesting that these deficits are specific to the domain of visual motion and do not result from a broader visual or attentional deficit. Further evidence for the specificity of these motion deficits is provided by their robustness to controlling for ADHD symptoms as gleaned from a standard self-report checklist.

Performance of coherent motion detection and velocity discrimination may rely upon distinct neural mechanisms that are mediated in overlapping brain areas. Both coherent motion detection and velocity discrimination tasks (see Figure 1) assess sensitivity to motion information, and performance on both is known to depend critically upon neural activation in brain area MT+/V5 (Culham, He, Dukelow, & Verst-raten, 2001; Braddick, O'Brien, Wattam-Bell, Atkinson, & Turner, 2000; Braddick et al., 2001). However, performance on these tasks may depend as well upon activation in other brain areas, for example, in the cerebellum (Nicolson et al., 2001; Nawrot & Rizzo, 1995; Nawrot & Rizzo, 1998). In addition, the neural computations required by these two tests may be different. For example, detection of coherent motion requires spatial integration of motion information in the presence of visual noise, whereas a typical velocity discrimination task such as ours requires quantitative estimation of localized motion signals and a fine comparison of the two different motion signals. Because our study assessed motion processing using both of these complementary methods, it is in a position to make a stronger statement than previous studies about potential neural underpinnings of motion processing deficit in dyslexia. In particular, our finding of a dissociation between motion processing deficits on these two tasks suggests that they reflect underlying deficits either in distinct brain areas, or of distinct functions mediated within the same brain area.

## RESULTS

### Poorer Performance by Dyslexic Participants on Motion Processing Measures

The analyses reported in this subsection demonstrate that our dyslexic participants performed more poorly than nondyslexic participants on two different motion processing tasks, and that these group differences held even after controlling for performance on visual processing control tasks, general skills measures, and self-reported attention deficit symptoms.

Dyslexic participants (see Table 1 and Figure 2) performed more poorly than nondyslexic participants on

both the coherent motion detection task,  $t(34) = 2.69$ ,  $p = .01$ , and the velocity discrimination task,  $t(34) = 2.45$ ,  $p = .02$ .

Dyslexic participants also performed more poorly on the contrast detection for stationary gratings task,  $t(34) = 2.13$ ,  $p = .05$ , one of the control tasks for velocity discrimination. There were no statistically significant differences between groups on the other three control tasks. Discriminant analysis was able to classify 67% of participants as dyslexic or nondyslexic based on their scores from the coherent motion detection task (63% sensitivity, 71% specificity), 63% based on scores from the velocity discrimination task (68% sensitivity, 59% specificity), and 75% based on scores from both tasks together (79% sensitivity, 71% specificity).

Two separate analyses of covariance (ANCOVAs), one for each motion task, were used to determine if motion processing group differences were robust to controlling for scores on visual processing control tasks. For each analysis, one motion processing task was entered as the dependent variable, its matched visual processing control task(s) were included as covariates, and group membership (control or dyslexic) was included as a fixed independent variable. Group differences remained significant both for coherent motion detection,  $F(1,33) = 10.291$ ,  $p = .003$ , and for velocity discrimination,  $F(1,31) = 4.601$ ,  $p = .04$ .

A second pair of ANCOVAs, again one for each motion task, was used to determine if motion processing group differences were robust to controlling for Wechsler Adult Intelligence Scale—Revised (WAIS-R) measures of general cognitive skill in addition to the visual processing control tasks. For each analysis, one motion processing task in turn was entered as the dependent variable; this time its matched visual processing control task(s) and WAIS-R subtests were included as covariates, and group membership was as before included as a fixed independent variable. When all six WAIS-R subtest scores were included, group differences remained marginally significant for velocity discrimination,  $F(1,25) = 4.015$ ,  $p = .056$ , while being rendered nonsignificant for coherent motion detection,  $F(1,27) = 1.480$ ,  $p = .234$ . It is however well known that dyslexic persons tend to perform poorly on the digit span WAIS-R subtest (Brosnan et al., 2002; Witton et al., 1998; Vargo, Grosser, & Spafford, 1995; Swanson, 1994; Mishra, Ferguson, & King, 1985); thus, controlling for this measure may be inappropriately carving out an essential aspect of dyslexia (see Miller & Chapman, 2001; Meehl, 1971). Indeed, digit span was significantly associated with coherent motion detection across all participants,  $r(34) = 0.502$ ,  $p = .002$ , and when digit span was eliminated from the above ANCOVA analysis that controlled for WAIS-R performance, coherent motion detection group differences became significant again,  $F(1,28) = 4.238$ ,  $p = .05$ . These analyses show that group differences in motion process-

**Table 1.** Performance of Control and Dyslexic Participants on All Measures (Values are Mean ± Standard Deviation)

<i>Measure (Unit), N = 36 (except Where Noted)</i>	<i>Control (n = 17)</i>	<i>Dyslexic (n = 19)</i>	<i>t test</i>	<i>Effect Size Pearson's r</i>
Age (years)	31.00 ± 9.97	31.00 ± 7.86	<i>ns</i>	.00
<i>Visual motion tasks with matched control tasks</i>				
Velocity Discrimination (contrast sensitivity)	115.47 ± 51.87	80.00 ± 33.87	**	.39
Orientation Discrimination (contrast sensitivity)	109.06 ± 21.68	98.68 ± 27.03	<i>ns</i>	.21
Contrast Detection—Moving Grating (contrast sensitivity)	361.24 ± 94.14	332.53 ± 72.92	<i>ns</i>	.17
Contrast Detection—Stationary Grating (contrast sensitivity)	163.35 ± 33.54	143.00 ± 23.44	*	.34
Coherent Motion Detection (percent coherence)	7.25 ± 3.85	10.76 ± 3.98	**	.42
Coherent Form Detection (percent coherence)	19.58 ± 4.94	18.72 ± 3.91	<i>ns</i>	.10
<i>Cognitive skills measures (all from Wechsler Adult Intelligence Scale—R [WAIS-R])</i>				
1) Similarities	113.24 ± 9.83	118.95 ± 12.54	<i>ns</i>	.25
2) Vocabulary	117.06 ± 11.73	115.79 ± 16.61	<i>ns</i>	.05
3) Picture Arrangement	110.00 ± 12.99	106.58 ± 12.81	<i>ns</i>	.14
4) Block Design	119.12 ± 10.19	112.11 ± 10.84	<i>ns</i>	.32
5) Digit Span	111.76 ± 16.20	92.11 ± 10.84	***	.60
6) Digit Symbol	114.12 ± 12.53	98.42 ± 14.15	***	.52
<i>General reading skills measures (reading and spelling from Wide Range Achievement Test—R [WRAT-R]; reading rate from Nelson–Denny Reading Test):</i>				
Reading—Single-word pronunciation	113.41 ± 10.72	96.58 ± 16.94	***	.52
Spelling	115.24 ± 8.64	93.00 ± 11.39	***	.75
Reading Rate (scaled score)	211.18 ± 22.45	181.58 ± 9.72	***	.67
<i>Reading subskills measures</i>				
Phonological Choice (no. incorrect)	3.50 ± 2.56	16.16 ± 12.29	***	.59
Orthographic Choice (no. incorrect)	1.38 ± 1.63	5.32 ± 3.30	***	.64
Irregular Word Reading (no. incorrect)	0.69 ± 0.95	2.47 ± 2.83	***	.52
Pseudoword Reading (no. incorrect)	1.56 ± 1.46	5.33 ± 4.19	***	.50
Phonological Choice—mean response time (msec)	3282 ± 771	4232 ± 1443	*	.33
Orthographic Choice—mean response time (msec)	1029 ± 257	1229 ± 278	*	.36
Irregular Word Reading (sec)	17.91 ± 4.58	26.95 ± 6.89	***	.58
Pseudoword Reading (sec)	23.55 ± 5.38	42.13 ± 15.53	***	.63
<i>Self-report scales</i>				
Inattention (CAARS) <i>n</i> = 26	15.50 ± 6.64	14.94 ± 5.63	<i>ns</i>	.04
Hyperactivity (CAARS) <i>n</i> = 26	17.10 ± 8.08	16.63 ± 6.38	<i>ns</i>	.03
Impulsivity (CAARS) <i>n</i> = 26	15.80 ± 8.28	11.69 ± 6.51	<i>ns</i>	.23
Dyslexic Characteristics (ADO) <i>n</i> = 26	4.40 ± 2.22	10.75 ± 3.86	***	.69

*ns* = not significant.

Standard scores (computed for Wechsler) = normed score based on population mean of 100 and the population standard deviation is 15.

\**p* < .02.

\*\**p* < .05.

\*\*\**p* < .002.

ing are generally robust to controlling for general cognitive skills, though group differences in the WAIS-R digit span measure run somewhat parallel to those on coherent motion detection.

A final pair of analyses was carried out in which ADHD scores were added as covariates to the above analyses (missing ADHD values were replaced with means in order to retain adequate statistical power). Results remained nearly identical, suggesting that reported differences in ADHD characteristics do not moderate the above findings.

The following variables among those included in Table 1 had distributions that differed sufficiently from normality (Kolmogorov–Smirnov  $Z$ ,  $p < .10$ ), so their scores were normalized using the Blom ranking procedure before being included in any analysis: accuracy measures on the Phonological Choice, Irregular Word Reading, and Pseudoword Reading tests, speed measure on the Pseudoword Reading Test, and score on the WAIS-R picture naming subtest. Following these normalizations, no data showed inequality of variance across groups (Levene’s Test,  $p > .05$ ). All group-comparison analyses were carried out a second time considering the velocity discrimination task and its control tasks on a log scale, despite the skew that this introduced to the data, as this was a common method for analyzing contrast sensitivity data. Results were qualitatively identical to those obtained using the linear scale. Cook’s distances calculated for all analyses reported both above and below indicated (all  $D < .37$ ) that no single data points disproportionately affected any results.

As an extra check against outlying data points affecting results, the  $t$  test demonstrating group differences on the velocity discrimination task was repeated after removing the top scoring dyslexic subject and the top scoring nondyslexic subject. Then this  $t$  test was repeated iteratively, each time removing the next top scoring dyslexic subject and the next top scoring nondyslexic subject, until one third of subjects (12 total) had been removed. This same analysis was repeated removing the bottom scorers rather than the top scorers, and all such analyses were repeated for the coherent motion detection task as well. The Pearson  $r$  effect-size for each of these analyses increased as more subjects were removed, exactly the opposite pattern of results that would have been expected if strikingly high or low scorers were contributing to the observed group differences.

### **Selective Associations between Coherent Motion Detection and Accuracy, and between Velocity Discrimination and Speed, on Reading Subskills Tests**

The analyses reported in this subsection suggest that our reading subskills measures dissociate naturally into an

accuracy factor and a speed factor, and that these factors show selective associations with coherent motion detection and velocity discrimination, respectively.

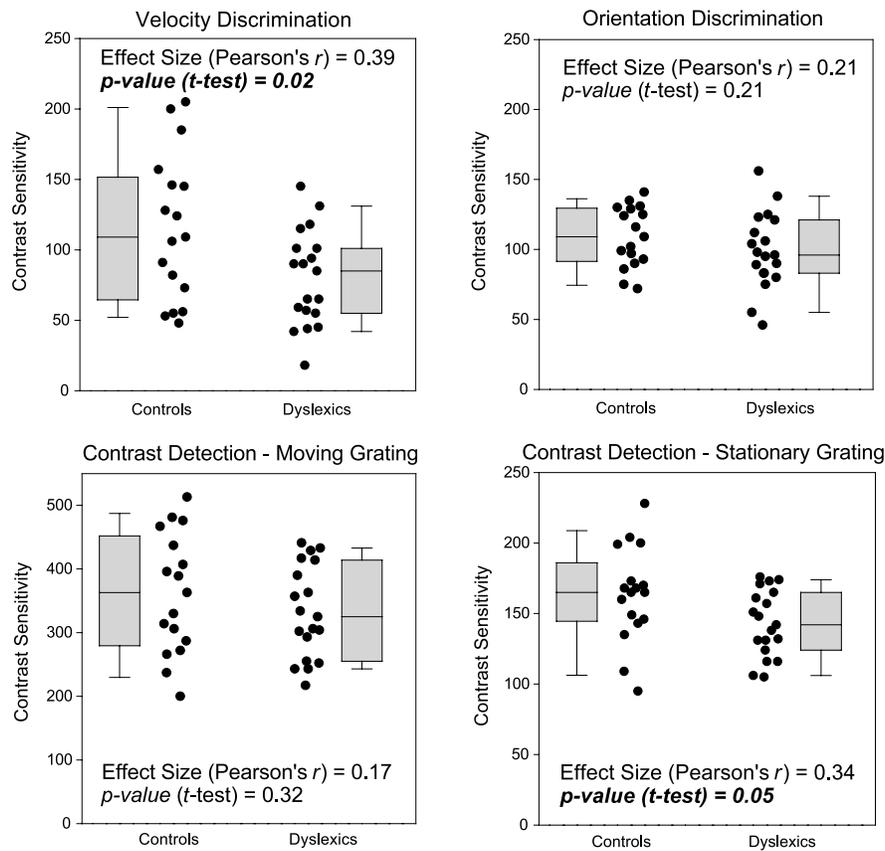
Partial correlations among all participants were used to examine general relationships between motion processing and reading subskills. Separate analyses were done for each motion task, with that motion task’s matched visual processing control task(s) included as controlled-for variables, and partial correlations then computed between that motion task and each of the eight reading subskills measures (see Table 2).

Because all correlations had an expected direction, and this analysis was mainly directed toward uncovering general patterns of correlation, one-tailed tests of significance were used. Velocity discrimination correlated significantly with the speed measures on all four reading subskills tasks yet did not correlate with any of the corresponding accuracy measures. Conversely, coherent motion detection correlated significantly with the accuracy measures on all four reading subskills tasks, yet it only correlated with irregular word reading among the corresponding speed measures, and the latter was a lower correlation than that between irregular word reading and velocity discrimination.

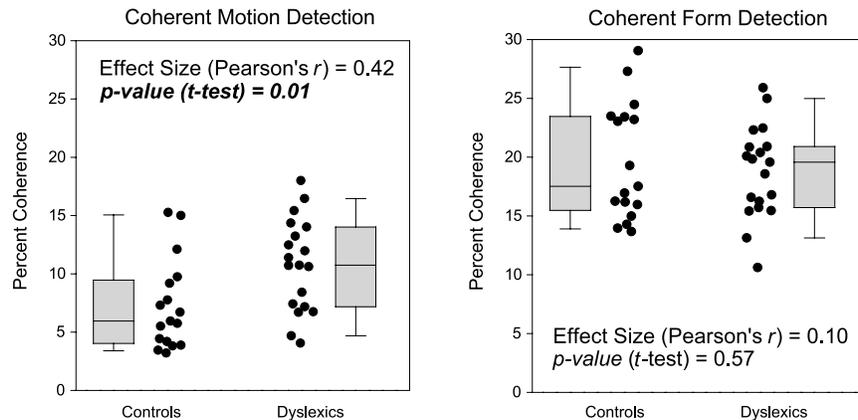
Upon observing these selective associations, we ran an exploratory factor analysis to probe the hypothesis that the reading subskills measures would dissociate naturally into a speed factor and an accuracy factor, and that these factors would be associated selectively with velocity discrimination and coherent motion detection, respectively. A principal components analysis run on the speed and accuracy measures for each of the four reading subskills measures extracted two factors with eigenvalues above 1.0 (4.4 and 1.6, next largest being 0.6), providing support for the idea that there are two underlying factors of particular salience among these measures. A varimax rotation was then used to generate scores for each participant on these two factors. All accuracy-related variables loaded highly significantly ( $p < .001$ ) on the first factor, whereas only two of the four speed-related variables loaded significantly on this factor (irregular word naming and nonword naming,  $p < .001$ ), and both to a lesser degree than any of the accuracy-related variables. Conversely, all speed-related variables loaded significantly ( $p < .005$ ) on the second factor, whereas none of the accuracy-related variables loaded significantly on this factor. Thus, the first factor might reasonably be considered an accuracy factor, and the second a speed factor.

When regression scores were generated for these two factors and correlations were performed across all participants, scores for the “accuracy” factor correlated strongly with coherent motion detection,  $r(34) = 0.47$ ,  $p = .004$ , yet not with velocity discrimination,  $r(34) = 0.14$ ,  $p = .43$ ; whereas scores for the “speed”

## Velocity Discrimination Task and Three Control Tasks:



## Coherent Motion Task and Control Task:



**Figure 2.** Box plots and individual data points indicating performance by dyslexic and control participants on visual processing tasks. Note that lines within box plots depict group medians, box edges define the 25th and 75th percentiles, and whisker edges define the 5th and 95th percentiles for these data (there are no statistical outliers).

factor correlated strongly with velocity discrimination,  $r(34) = 0.52$ ,  $p = .001$ , yet not with coherent motion detection,  $r(34) = 0.15$ ,  $p = .38$ . A remarkably similar pattern of results was obtained when all above analyses were constrained to just the dyslexic group,  $r_s(19) = 0.47, 0.24, 0.38, 0.24$ ,  $p_s = 0.04, 0.32, 0.10,$

$0.33$ , respectively), though note that the association between velocity discrimination and the “speed” factor is highest when considered across all participants, suggesting that it may generalize most strongly to a broad population including persons with a wide range of reading abilities.

**Table 2.** Partial Correlations between Visual Motion Processing Tasks and Reading Subskills Measures (Controlling for Performance on Matched Visual Processing Control Tasks) across All Participants

Measure (unit), $n = 36$	Velocity Discrimination (Contrast Sensitivity)	Coherent Motion Detection (Percent Coherence)
<i>Reading subskills measures</i>		
Phonological Choice (no. incorrect)	$r = -.12$ ( $p = .26$ )	$r = .58$ ( $p = .0005$ )
Orthographic Choice (no. incorrect)	$r = -.28$ ( $p = .06$ )	$r = .34$ ( $p = .02$ )
Irregular Word reading (no. incorrect)	$r = -.10$ ( $p = .29$ )	$r = .42$ ( $p = .006$ )
Pseudoword reading (no. incorrect)	$r = -.07$ ( $p = .35$ )	$r = .44$ ( $p = .004$ )
Phonological Choice—mean response time (msec)	$r = -.45$ ( $p = .005$ )	$r = 0.00$ ( $p = .50$ )
Orthographic Choice—mean response time (msec)	$r = -.44$ ( $p = .005$ )	$r = 0.03$ ( $p = .44$ )
Irregular Word reading (sec)	$r = -.48$ ( $p = .002$ )	$r = .38$ ( $p = .01$ )
Pseudoword reading (sec)	$r = -.28$ ( $p = .05$ )	$r = .18$ ( $p = .15$ )

Significant correlations (one-tailed) are indicated in **bold** type.

Note that since higher scores indicated better performance for Velocity Discrimination, yet worse performance for Coherent Motion Detection, the expected directions of correlations are reversed for these two tasks.

### Two Distinct Motion Processing Deficits

Two additional analyses confirmed the dissociation between the two motion processing deficits found in this study. First a simple correlation between coherent motion detection and velocity discrimination was non-significant across all participants,  $r(34) = -0.13$ ,  $p = .44$ , remaining so after controlling via partial correlation for performance on the four visual processing control tasks,  $r(30) = -0.22$ ,  $p = .22$ , and also remaining so when these two analyses were confined to the dyslexic group,  $r(17) = 0.06$ ,  $p = .80$  and  $r(13) = -0.11$ ,  $p = .70$ , respectively.

Second, in two ANCOVA analyses, group differences in coherent motion detection remained significant after controlling for velocity discrimination,  $F(1,33) = 6.373$ ,  $p = .02$ , and group differences in velocity discrimination remained significant after controlling for coherent motion detection,  $F(1,33) = 5.227$ ,  $p = .03$ . Taken along with the finding described above that coherent motion detection correlates selectively with accuracy, and velocity discrimination correlates selectively with speed on reading subskills tasks, these findings support the idea that the two dyslexic motion processing deficits observed in this study are distinct from each other.

### Subtype Analysis

Given the evidence above for two distinct motion processing deficits associated with different reading subskills deficits, a final analysis was done to probe the extent to which two subtypes of dyslexia could be identified among our participants. We added together  $z$  scores for coherent motion detection and for the reading subskills accuracy factor (derived above) to form

a “motion-detection/reading-accuracy” composite score, and  $z$  scores for velocity discrimination and the reading subskills speed factor were added together to form a “velocity-discrimination/reading-speed” composite score. Fourteen of the 19 dyslexic participants scored more than one standard deviation worse than the control mean on the former, and eight did so on the latter. In all, 18 of the 19 dyslexic participants scored more than one standard deviation worse on at least one of the two measures, and five did so on both. Thus, preliminary evidence is provided for a larger “motion-detection/reading-accuracy” dyslexic subtype, and for a smaller “velocity-discrimination/reading-speed” subtype.

## DISCUSSION

### Two Motion Processing Deficits and Associated Reading Deficits

This study provides evidence that there are in fact two distinct motion processing deficits in dyslexia, rather than one as assumed by previous research, and that each of these deficits is associated with a different type of reading deficit. A deficit in detecting coherent motion is selectively associated with low accuracy on reading subskills tests, and a deficit in discriminating velocities is selectively associated with slow performance on these same tests. These findings are consistent with a growing literature that focuses upon reading speed and fluency deficits as well as accuracy deficits in dyslexia (Kronbichler et al., 2002; Nicolson et al., 2001; Wolf & Bowers, 1999; Lovett, 1984; Bakker, 1979).

The motion processing deficit findings in the present study replicate previous reports of deficits for coherent motion detection (Hansen et al., 2001; Ridder et al.,

2001; Everatt et al., 1999; Slaghuis & Ryan, 1999; Raymond & Sorenson, 1998; Talcott, et al., 1998; Talcott, Hansen, et al., 2000; Witton et al., 1998; Cornelissen et al., 1995; Pelli & Zhang, 1991) and velocity discrimination (Demb, Boynton, Best, et al., 1998) in dyslexia, as well as those of associations between coherent motion detection and accuracy of performance on measures of both phonological skill (Talcott et al., 1998, 2002; Witton et al., 1998) and orthographic skill (Talcott et al., 2002; Talcott, Witton, et al., 2000; Cornelissen, Hansen, Gilchrist, et al., 1998; Cornelissen, Hansen, Hutton, et al., 1998). The broader array of motion tasks as well as reading subskills tasks administered to our participants allowed us to both establish a dissociation between these two motion processing deficits and detect selective associations between motion processing performance and reading subskills. We also assessed the degree to which we could classify our dyslexic participants based upon the latter associations: About half of our dyslexic participants had particular difficulties with reading accuracy and coherent motion detection, a sixth with reading speed and velocity discrimination, and a quarter with both groups of deficits. Our findings from this classification analysis as well as our “selective association” analysis suggest that associations between coherent motion detection and reading accuracy may generalize most strongly to populations of dyslexic readers, whereas associations between velocity discrimination and reading speed may generalize most strongly to broader populations, including persons with a wide range of reading abilities. In the context of present results it is interesting to note that the single reported failure to replicate a dyslexic deficit for coherent motion detection (Kronbichler et al., 2002) used dyslexic persons characterized principally by a deficit of fluency, those who might in the context of our results be predicted to perform poorly at velocity discrimination but normally at coherent motion detection.

In addition to establishing the presence of two distinct motion processing deficits in dyslexia, this study builds upon previous findings by providing evidence against a number of possible alternative explanations for poor performance on motion processing tasks. First and foremost, this study uses well-matched visual processing control tasks to better isolate the motion processing capacities of interest (note that the coherent form detection task has been used in one previous study: Hansen et al., 2001). Motion processing deficits are found even after controlling statistically for performance on the latter tasks, suggesting that these motion processing deficits are specific to the domain of visual motion, and do not result from a broader visual or attentional deficit. Additionally, self-report measures of ADHD symptoms administered to a subset of participants show both that groups seem well matched on these characteristics and that controlling statistically for

these scores does not reduce the size of either observed motion processing deficit. The latter findings provide additional evidence that motion deficits do not result from the sort of generalized attention deficit commonly comorbid with developmental dyslexia. Lastly, it should be noted that coherent motion detection deficits run somewhat parallel to deficits observed on one of the general cognitive measures, the WAIS-R digit span subtest, suggesting that some common process may be involved in both of these deficits.

### Hypotheses of Underlying Mechanism

In addition to strengthening the evidence for motion processing deficit in dyslexia and identifying new associations between motion processing and reading subskills deficits, our data suggest a novel hypothesis regarding the neural underpinnings of this motion deficit. A wide body of literature ties both types of motion processing tasks to the same brain area, MT+/V5 (Culham et al., 2001; Braddick et al., 2000, 2001), and previous neuroimaging research in dyslexia has tied motion processing deficits to this brain area (Demb et al., 1997; Demb, Boynton, & Heeger, 1998; Vanni et al., 1997; Eden et al., 1996), both suggesting a common neural and functional substrate to dyslexic deficits on these tasks. However, our finding of a dissociation between deficits on these tasks supports the idea that they reflect either deficits of two distinct functions mediated within the same brain area(s), or deficits within separable brain areas. In this context, future inquiry might attempt to differentially tie dyslexic deficits in coherent motion detection and velocity discrimination to suggested brain areas such as MT+/V5, the cerebellum (Nicolson et al., 2001; Nawrot & Rizzo, 1995; Nawrot & Rizzo, 1998), and the lateral geniculate nucleus (Stein, Talcott, & Walsh, 2000; Stein & Walsh, 1997; Livingstone et al., 1991; cf. Skottun, 2000a, 2000b).

Ultimately, one would of course hope to identify functional as well as physiological substrates of dyslexic motion processing deficits and their associated reading deficits. A first step toward this goal is to note the key differences between the tasks used to identify said motion processing deficits. For example, coherent motion detection relies on an ability to spatially integrate information and extract visual signal from noise, and velocity discrimination relies on an ability to quantitatively monitor visual input and make fine visual comparisons. It may be that the former abilities play some role in accurate representation of written language, whereas the latter play some role in fluency of processing of written language. However, there are other visual processes differentially tapped by these two motion tasks as well (see, e.g., Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001), and isolating which of these are responsible for the observed deficits and their reading-skill associates could be an important goal for future inquiry.

Any hypothesized causal mechanism involving motion processing and dyslexia must be viewed at this stage as speculative. However, in light of mounting evidence for relatively poor motion processing of various types among dyslexic persons, it is instructive to consider the plausibility of such a mechanism. Perhaps the most clearly stated of such hypotheses (Stein, 2001) makes reference to the important role that the visual motion system appears to play in the stabilization of perception. It has been proposed that despite the constant wandering of a visual scene on the retina created by unintentional eye drift, our visual percept is stabilized using corrective inputs from the visual motion system (Murakami & Cavanagh, 1998, 2001). Stein (2001) proposes that an inefficient motion processing system could lead to a less stable percept, reports of which are a common complaint among dyslexic children (Stein & Fowler, 1981). This might also lead to less comfortable, less accurate, and/or less fluent reading (Stein, 2001). Given that Murakami and Cavanagh (2001) have provided evidence that the neural locus of a motion mediated visual stabilization mechanism exists in “some extrastriate motion area along the parietal pathway including [MT+/V5],” this could point to MT+/V5 as an area of particular interest in the search for neural loci of one or more motion deficits in dyslexia.

## Conclusions

This study demonstrates the existence of two distinct motion processing deficits in dyslexia, rather than one as assumed by previous research, and shows that each of these deficits is associated with a different type of reading deficit. Both motion deficits are shown to be specific to the domain of visual motion, and not the result of a generalized deficit of vision or attention. It may be that each of these patterns of deficit reflects a distinct underlying neurocognitive mechanism of dyslexia.

## METHODS

### Subjects

Thirty-six adults between the age of 18 and 48 participated in this research. Nineteen had previously been diagnosed as developmentally dyslexic and 17 were recruited as nondyslexic controls. The mean age of the dyslexic group,  $M(19) = 31$  years,  $SD = 7.86$ , matched that of the control group,  $M(17) = 31$  years,  $SD = 9.97$ . Subjects were recruited from two local universities, from a local dyslexia support group, and via a website. All participants had corrected-to-normal vision, and none had been identified as having a neurological disorder. No nondyslexic participant reported any history of reading difficulties.

All dyslexic participants had been diagnosed in the past on the basis of a substantial discrepancy between general reading skills and other cognitive skills, also known as specific reading disorder. Group differences on cognitive and reading measures (see Table 1) were probed to determine how well dyslexic participants currently fit such a profile. The dyslexic group, as consistent with the dyslexia literature, scored significantly lower than the nondyslexic group on the digit span and digit symbol measures of cognitive skill (Brosnan et al., 2002; Witton et al., 1998; Vargo et al., 1995; Swanson, 1994; Mishra, et al., 1985). There were, however, no significant group differences on the similarities, vocabulary, picture arrangement, or block design cognitive skill measures. As expected, the dyslexic group scored significantly lower than the nondyslexic group on the Wide Range Achievement Test—Revised (WRAT-R) measures of spelling and single word pronunciation. We calculated the discrepancy in standard deviation units between general reading skills (the average of the two WRAT-R subtests) and cognitive skills (first using the average of all six WAIS-R subtests, then using the average of the following four subtests: similarities, vocabulary, picture arrangement, and block design). As expected, using both the six-subtest cognitive skills measure, dyslexic  $M = 0.84$ ,  $SD = 0.89$ ; nondyslexic  $M = -0.01$ ,  $SD = 0.47$ ;  $t(34) = 3.494$ ,  $p < .001$ , and the four-subtest cognitive skills measure, dyslexic  $M = 1.24$ ,  $SD = 0.88$ ; nondyslexic  $M = -0.04$ ,  $SD = 0.39$ ;  $t(34) = 5.389$ ,  $p < .001$ , dyslexic participants demonstrated highly significantly more discrepancy than nondyslexic participants. Using the four-subtest cognitive skills measure, we found that 11 dyslexic participants had a discrepancy larger than 1.0, and 2 of these had a discrepancy larger than 2.0 standard deviations; using the six-subtest measure, we found these numbers were 7 and 2, respectively.

It appears from these data that some dyslexic participants had managed to at least partially compensate over time to a point where their general reading skills had begun to catch up with their cognitive skills. Consistent with the idea that those dyslexic participants without substantial discrepancies at the time of testing still showed persistent deficits, discriminant analyses showed that 81% of all participants could be correctly classified as dyslexic or nondyslexic based upon their rate of reading score alone (reading rate deficits commonly persist even in well-compensated dyslexic persons), and this figure rose to 100% with the inclusion of the speed and accuracy measures from the Phonological Choice task. Moreover, 8 of the 11 reading measures used in this study were able singly to classify more than 75% of participants, and 9 of 11 measures discriminated the groups with a Pearson's  $r$  effect-size at or above 0.5 and a  $p$  value below .002. Furthermore, dyslexic participants reported substantially more,  $t(25) = 5.324$ ,  $p < .0001$ , dyslexia-associated characteristics than did

nondyslexic participants on the Adult Dyslexia Organization (ADO) checklist. There were no significant group differences on any of the core ADHD scales (inattention, impulsivity, and hyperactivity), suggesting that the dyslexic group did not demonstrate these symptoms to a greater degree than the control group.

## Visual Processing Tests

### *Velocity Discrimination and Control Tasks*

This testing paradigm was similar to that used by Chen et al. (1999). It consisted of four tasks (see Figure 1): velocity discrimination, orientation discrimination, contrast detection for a moving stimulus, and contrast detection for a static stimulus. Velocity discrimination required participants to identify the faster of two sequentially presented stimuli. Orientation discrimination required participants to identify the less vertical of two sequentially presented stimuli. The two contrast detection tasks required participants to identify which of two sequential periods contained a stimulus, the other period being blank. The velocity discrimination task was the main task of interest, while the other three tasks served as controls.

For each task, all non-contrast-stimulus parameters (e.g., velocity, orientation) were held constant, while task difficulty was modulated by changing the contrast of the stimuli. Stimulus contrast started at 1.5% contrast, a level easily visible to all participants. It was then decreased by 30% of its previous value after each three consecutive correct responses, and increased by 30% of its previous value for each incorrect response. This procedure converges on the level of contrast that produces performance at 79.4% accuracy. The task continued until the direction of contrast change (i.e., from increasing to decreasing or vice versa) had switched 12 times. Then the mean contrast value for those 12 switches was calculated. The reciprocal of this mean contrast value was used for all analyses reported in this paper. Note that the reciprocal of a contrast value is referred to by convention as contrast sensitivity, and increases with better performance (e.g., contrast of 0.005 = 0.5% contrast = contrast sensitivity of 200). Participants were given several minutes of practice before performing each task. All participants were given the option of identifying target stimuli either verbally or with key presses.

Testing was conducted in a darkened room. Stimuli were presented on a black and white computer monitor adapted with a luminance attenuator, which allowed for fine gradations in luminance (Pelli & Zhang, 1991). All stimuli were gratings with a sinusoidal spatial luminance distribution of spatial frequency 0.5 cycles/deg and were shown through a circular window subtending 19° of visual angle with a space average luminance of 40 cd/m<sup>2</sup>. The duration of each stimulus was 300 msec with sudden onset and offset, and the interval between two compar-

ison stimuli was 500 msec. All gratings (see Figure 1) were vertical (90°) except for the nonvertical (86°) orientation discrimination stimulus. The velocity discrimination stimuli moved at 11°/sec and 9°/sec, and the moving contrast detection stimulus moved at 10°/sec.

We administered orientation discrimination, static contrast detection, and moving contrast detection tasks as controls for generalized attention and memory capacity, base contrast sensitivity, and ability to discriminate two visual stimuli per se. With regard to the first of these, the demands upon attention and memory for these tasks are similar to that for the velocity discrimination task, so any deficit in this domain should affect the tasks relatively equally. With regard to the second, the measurement of base contrast sensitivity to moving and static stimuli allowed these values to be factored out from velocity and orientation discrimination measurements, respectively (this is important since contrast sensitivity was the index of performance used on these tasks). With regards to the third, the orientation discrimination task provides an index of visual discrimination not involving motion signals, so any deficit in visual discrimination per se should have hindered performance on this task as well as on the velocity discrimination task.

### *Coherent Motion Detection and Control Tasks*

This testing paradigm (see Figure 1) was similar to that used in Hansen et al. (2001). It consisted of a coherent motion detection task and a coherent form detection control task. Coherent motion detection required participants to identify which of two simultaneously presented rectangular patches contained dots moving in concert among randomly moving dots. Coherent form detection required participants to identify which of two simultaneously presented rectangular patches contained, among randomly oriented lines, lines placed in tangent to imaginary concentric circles radiating out from a central point. For both tasks, stimulus coherence (i.e., the percentage of dots/lines which served as signal among noise dots/lines) started at 66.7%, a level easily visible to all participants, this was then decreased by 1 dB (a factor of 1.122) with each correct response, and increased by 3 dB (a factor of 1.412) with each incorrect response. This form of weighted staircase procedure was proposed by Kaernbach (1991). The task continued until the direction of coherence change (i.e., from increasing to decreasing or vice versa) had switched eight times. Then the geometric mean was taken of the coherence present at the final six of these eight switches. This procedure converges on the level of coherence that produces performance at 75% accuracy. Participants were given several trials of practice on each task; then they performed each task three times. All analyses below use the average of these three scores for each participant on a given task. All participants were given the option of

identifying target stimuli either verbally or with key presses. An alpha statistic was computed to probe the test–retest reliability of the tasks: the coherent motion detection task demonstrated good reliability ( $\alpha = .80$ ), while the coherent form detection task demonstrated acceptable reliability ( $\alpha = .60$ ).

Testing was conducted in a darkened room. For the coherent motion detection task, two rectangular patches of 300 high-luminance ( $130 \text{ cd/m}^2$ ) white dots (1 pixel) were presented side by side on the black background of a computer monitor. Each patch subtended  $10^\circ \times 14^\circ$  visual angle and the patches were separated by  $5^\circ$ . In one patch, all dots moved in randomly changing directions in a Brownian manner for 2.3 sec. In the other patch (the “target” patch), some of the dots moved in this same random fashion, but a certain percentage moved coherently (at  $7^\circ/\text{sec}$ ) back and forth together. Each dot disappeared then immediately reappeared at a randomly chosen different location every 86 msec (three software animation frames of 28.6 msec each) to prevent tracking of individual dots. All measures of coherence were corrected for finite dot lifetimes so that in the case where all dots were moving coherently, and each had a lifetime of three frames, this was described as 67% coherence. Global direction switched from left to right (or vice versa) every 858 msec until 2288 msec was reached. Participants indicated at the end of the 2288 msec which patch had contained the coherently moving dots. Parameters for the coherent form task were identical to those for the coherent motion task except that instead of moving dots, each patch in this task contained 900 static, high-luminance,  $0.4^\circ$  long line segments. In the nontarget patch these were randomly oriented, while in the target patch a certain percentage were placed in tangent to imaginary concentric circles radiating out from a central point.

We administered the coherent form detection task as a control both for generalized spatial attention and for visual detection ability per se. With regard to the former, both tasks require a similar degree of spatial monitoring, and thus have similar spatial attention demands. Thus, a deficit in spatial attention should have hindered performance on both tasks similarly. With regard to the second, the coherent form detection task provides an index of visual detection not involving motion signals, so any deficit in visual detection per se should have hindered performance on this task as well as the coherent motion detection task.

### Psychometric Tests

Each participant was evaluated by a battery of cognitive skills, general reading skills, and reading subskills tests, and an unselected subset of participants was administered self-report checklists to assess ADHD symptoms and dyslexia-associated traits.

Cognitive skills were assessed with the following six subtests from the WAIS-R (Wechsler, 1981): Similarities (verbal reasoning), Vocabulary (defining words), Picture Arrangement (decoding temporally shuffled picture narrative), Block Design (constructing spatial patterns from component parts), Digit Span (hearing then repeating back sequences of numbers), and Digit Symbol (quickly matching novel symbols to numbers).

The assessment of general reading skills in this study was the spelling and the single word pronunciation subtests from the WRAT-R (Jastak & Wilkinson, 1984). A measure of accuracy is obtained for each subtest. Additionally, a measure of reading rate for normal prose was obtained using the Nelson–Denny Reading Test (Brown, Fishco, & Hanna, 1993). It is useful to assess reading rate because reading rate deficits may persist even in relatively well compensated dyslexic persons.

Reading subskills were probed with the following measures. Orthographic analysis was assessed using the Orthographic Choice Test (Talcott, Witton, et al., 2000). For this computer-based test, a correctly spelled word needs to be identified from a pair of identical-sounding—but differently spelled—words (e.g., rain vs. rane, the latter commonly known as a pseudohomophone). Phonological analysis was assessed using a computer-based task designed to look similar to the Orthographic Choice Test, which was dubbed the Phonological Choice Task. For this test, three misspelled words are presented (e.g., nite, kile, and hote) and participants identify the one that sounds like a real word (in this case, nite). Both of these tests were adapted from those described in an article by Olson, Forsberg, Wise, Rack, et al. (1994). Measures of speed and accuracy were obtained for both tests. In addition, the Irregular Word and Pseudoword tests from the Castles and Coltheart (1993) single-word reading battery were used. These tests require the speeded naming of 30 irregularly spelled words (e.g., colonel) and 30 pseudowords (e.g., dethix), respectively. The former putatively taps orthographic decoding skill, and the latter phonological decoding skill. Measures of speed and accuracy were obtained for these tests as well.

Finally, an unselected subset of 26 participants (16 dyslexic, 10 nondyslexic) were administered the Conners Adult ADHD Rating Scale—Long Version (CAARS-L) (Conners, Erhardt, & Sparrow, 1998), as well as the ADO checklist of dyslexia-associated traits (Schloss, 1996).

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