
Neural Systems for Compensation and Persistence: Young Adult Outcome of Childhood Reading Disability

Sally E. Shaywitz, Bennett A. Shaywitz, Robert K. Fulbright, Pawel Skudlarski, W. Einar Mencl, R. Todd Constable, Kenneth R. Pugh, John M. Holahan, Karen E. Marchione, Jack M. Fletcher, G. Reid Lyon, and John C. Gore

Background: *This study examined whether and how two groups of young adults who were poor readers as children (a relatively compensated group and a group with persistent reading difficulties) differed from nonimpaired readers and if there were any factors distinguishing the compensated from persistently poor readers that might account for their different outcomes.*

Methods: *Using functional magnetic resonance imaging, we studied three groups of young adults, ages 18.5–22.5 years, as they read pseudowords and real words: 1) persistently poor readers (PPR; $n = 24$); 2) accuracy improved (compensated) readers (AIR; $n = 19$); and 3) nonimpaired readers (NI, $n = 27$).*

Results: *Compensated readers, who are accurate but not fluent, demonstrate a relative underactivation in posterior neural systems for reading located in left parietotemporal and occipitotemporal regions. Persistently poor readers, who are both not fluent and less accurate, activate posterior reading systems but engage them differently from nonimpaired readers, appearing to rely more on memory-based rather than analytic word identification strategies.*

Conclusions: *These findings of divergent neural outcomes as young adults are both new and unexpected and suggest a neural basis for reading outcomes of compensation and persistence in adults with childhood dyslexia. Biol Psychiatry 2003;54:25–33 © 2003 Society of Biological Psychiatry*

Key Words: Dyslexia, reading disability, fMRI, outcome, compensation

From the Departments of Pediatrics (SES, BAS, WEM, KRP, JMH, KEM), Neurology (BAS), and Diagnostic Radiology (RKF, PS, RTC, JCG), Yale University School of Medicine, New Haven, Connecticut; Haskins Laboratories (WEM, KRP), New Haven, Connecticut; Department of Pediatrics, University of Texas-Houston Health Science Center (JMF), Houston, Texas; Child Behavior and Learning Branch, National Institute of Child Health and Human Development, National Institutes of Health (GRL) Bethesda, Maryland; and Department of Applied Physics, Yale University (JCG), New Haven, Connecticut.

Address reprint requests to Sally E. Shaywitz, Yale University School of Medicine, Department of Pediatrics, PO Box 3333, New Haven CT 06510-8064.

Received July 1, 2002; revised October 18, 2002; accepted October 28, 2002.

Introduction

Dyslexia is characterized by an unexpected difficulty in reading in children and adults who otherwise possess the intelligence and motivation considered necessary for accurate and fluent reading. It represents one of the most common problems affecting children and adults; in the United States, the prevalence of dyslexia is estimated to range from 5% to 17% of school-age children (Shaywitz 1998). There is now a strong consensus that the central difficulty in dyslexia reflects a deficit within the language system and, more particularly, in a lower level component, phonology, which has to do with the ability to access the underlying sound structure of words (Shaywitz 1998; Shaywitz 1996; Wagner and Torgesen 1987). In young school-age children, a deficit in phonology represents the most reliable and specific correlate of dyslexia (Fletcher et al 1994; Morris et al 1998). Such findings form the basis for the most successful and evidence-based interventions designed to improve reading (Report of the National Reading Panel 2000).

In this study, we wanted to learn whether and how two groups of young adults who were poor readers as children, a relatively compensated group and a group with persistent reading difficulties, differed from nonimpaired readers. In addition, we wanted to determine if there were any factors distinguishing the compensated from persistently poor readers that might account for their different outcomes. To this end, we took advantage of the availability of a cohort who are participants in the Connecticut Longitudinal Study, a representative sample that has been prospectively followed since 1983 when they were age 5 years and who have had their reading performance assessed yearly throughout their primary and secondary schooling (Shaywitz SE et al 1992; Shaywitz et al 1999; Shaywitz et al 1990).

Methods and Materials

Subjects

Three groups of young adults, ages 18.5–22.5 years, were classified as: 1) persistently poor readers (PPR; $n = 24$) if they

met criteria for poor reading in second or fourth grade and again in grade 9 or 10; 2) accuracy improved (compensated) readers (AIR; $n = 19$) if the subject satisfied criteria for poor reading in second or fourth grade and not in grade 9 or 10; and 3) nonimpaired readers (NI; $n = 27$) selected on the basis of not meeting the criteria for poor reading in any of the grades 2-10, having a reading standard score >94 (above the 40th percentile) to prevent overlap with the PPR and AIR groups, and having average Full Scale (FS) intelligence quotient (IQ) lower than 130 to avoid a supernormal control group. Poor reading was defined using the Weschler Intelligence Scale for Children-Revised (WISC-R) (Wechsler 1981) Full Scale IQ score and a composite of the two decoding subtests (Word Identification and Word Attack) from the Woodcock-Johnson Psycho-Educational Test Battery (Woodcock and Johnson 1977). At each grade, subjects were defined as poor reading if their FS IQ was ≥ 80 and actual score on the Woodcock-Johnson decoding composite was 1.5 standard errors below the predicted reading score (discrepancy definition) or decoding composite was <90 (low achievement definition). Both of these definitions validly identify children as poor readers, with little evidence for differences among subgroups of children formed with these definitions (Shaywitz BA et al 1992). The Yale University School of Medicine Human Investigation Committee approved the protocol, and informed consent was obtained from all subjects.

Functional Imaging

TASKS. We used functional magnetic resonance imaging (fMRI) to examine brain activation patterns while the subjects engaged in two visually presented tasks: 1) deciding whether two pseudowords rhymed (nonword rhyme [NWR]) (e.g., Do [LEAT] and [JETE] rhyme?) and 2) judging whether two real words were in the same category (CAT) (e.g., Are [CORN] and [RICE] in the same category?). A line judgment task (L) (e.g., Do [l] and [l] match?) was employed as a common baseline control condition. Subjects lay supine in the imaging system, looking up through a prism at a screen which was attached to the gantry; stimuli were projected on the screen using a MacIntosh G3 computer (Apple Computer, Cupertino, CA). Trials were 3575 milliseconds in duration; on each trial, stimuli were presented simultaneously for 2500 milliseconds followed by a blank screen. These tasks were presented in a block design, with nine epochs of the line task and eight epochs of either the NWR or CAT task within each run. Each block contained seven trials.

Proportion correct on the L, NWR, and CAT tasks were, respectively, for NI: .97, .88, .97; for AIR: .94, .81, .95; and for PPR: .90, .71, .90. Mean reaction times in milliseconds on the L, NWR, and CAT tasks were, respectively, for NI: 1261, 1553, 1333; for AIR: 1309, 1730, 1548; and for PPR: 1369, 1750, 1597. We did not examine correlations of activations with in-scanner performance. We designed the tasks to produce near-ceiling level performance, so variability was limited. Future analyses with this sample will examine correlations of activations with out-of-scanner behavioral measures, which are more standardized and sensitive measures.

fMRI PARAMETERS. Functional imaging was performed on a 1.5 Tesla Signa LX MR imaging system from General Electric

Medical Systems (Waukesha, WI). Before functional imaging, seven axial-oblique anatomic images were prescribed parallel to the intercommissural line based on sagittal localizer images. Axial-oblique images were obtained at the same relative slice location in each subject, extending from the inferior aspect of the temporal lobes to the parietal convexity. Activation images were collected using single shot, gradient echo, echo planar acquisitions (flip angle, 60°; echo time [TE], 60 milliseconds; repetition time [TR], 2685 milliseconds; field of view [FOV], 40 × 20 cm; 10-mm slice thickness; 128 × 64 × 1 number of excitations [NEX]) in the same slice locations used for anatomic images. In each of the imaging runs, 146 images per slice location were collected (after starting with four warm-up pulses to obtain magnetization equilibrium), while the subject performed the activation and baseline tasks described above. A single imaging run was acquired with each activation task and the interleaved baseline task, resulting in a total of 80 images per slice per activation task.

DATA ANALYSIS. Data analysis was performed using software written in MATLAB (MathWorks, Natick, MA). Before statistical analysis, the images from each run were motion corrected for three translation directions and for the three possible rotations (Friston et al 1996). Sixteen images at each slice location in a run were discarded to account for variation in signal intensity that occurred at the beginning of an echo-planar sequence from the hemodynamic changes in response to a task transition. The remaining images (130 images per slice location per run) were spatially filtered using a Gaussian filter with a full-width half-maximum (FWHM) value of 6.25 mm. Using t statistics corrected for linear drift (Skudlarski et al 1999), a t -value for each voxel in individual subjects was obtained by comparing images from the NWR task with the images from the Line task and by comparing images from the CAT task with images from the Line task. These t test comparisons were used to create activation maps that compared NWR-Line and CAT-Line for each subject. Both the activation maps and the anatomic images from individual subjects were transformed by in-plane transformation and slice interpolation into a normalized three-dimensional grid defined by Talairach and Tournoux (Talairach and Tournoux 1988).

The activation maps from individual subjects were used as a derived measure of task-related activity. The maps were combined by averaging the mean t -values of a voxel across subjects within each of the three groups. In this way, composite activation maps were obtained that compared NWR-Line and CAT-Line for NI, AIR, and PPR readers (Figure 1). To compare directly the NI, AIR, and PPR readers, the activation measure computed at each voxel for NWR and Line and for CAT and Line was compared across the three groups of readers (Figure 2). To avoid the need to assume a specific distribution and variance of the data, a randomization procedure was used to estimate p -values of the group composite maps (Manly 1997). To randomize, the sign of the activation measure for each voxel, which is the mean t -value, was reversed in randomly generated subsets of subjects. The activation measure was then recalculated. This procedure was repeated 1000 times, generating a distribution of the activation measure. The proportion of times that the observed activation measure was more extreme than a randomized value represents a

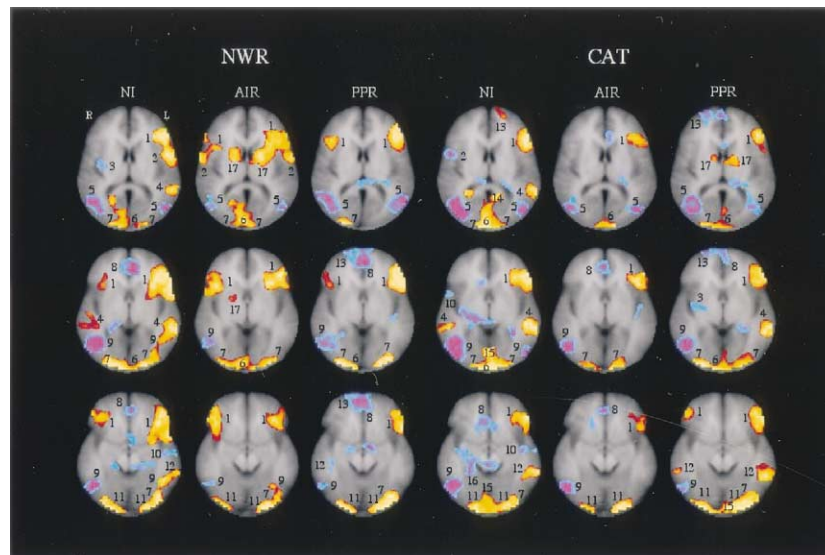


Figure 1. Composite maps demonstrating brain activation in NI, AIR, and PPR during nonword rhyme (NWR) and category (CAT) reading tasks. Red-yellow indicates areas that had significantly greater activation ($p = .05$) in the reading task compared to the line task. Blue-purple indicates areas that had significantly greater activation ($p = .05$) in the line task compared to the reading task. The slice locations for the top, middle, and bottom rows correspond to z levels of +12, +4, and -4, respectively, in the Talairach and Tournoux atlas (Talairach and Tournoux 1988). Following standard magnetic resonance imaging (MRI) nomenclature, the right side of the axial slice corresponds to the left hemisphere. The legend for regional brain activation is as follows: 1) inferior frontal gyrus, 2) precentral gyrus, 3) insula, 4) superior temporal gyrus and superior temporal sulcus, 5) middle temporal gyrus and superior temporal sulcus, 6) cuneus, 7) middle occipital gyrus, 8) anterior cingulate sulcus and adjacent aspects of the cingulate gyrus and superior frontal gyrus, 9) posterior middle temporal gyrus and anterior middle occipital gyrus, 10) anterior aspect of the superior temporal gyrus, 11) inferior occipital gyrus, 12) middle temporal gyrus, 13) superior frontal gyrus, 14) posterior cingulate gyrus, 15) lingual gyrus, 16) medial occipital temporal gyrus (parahippocampal region), and 17) basal ganglia.

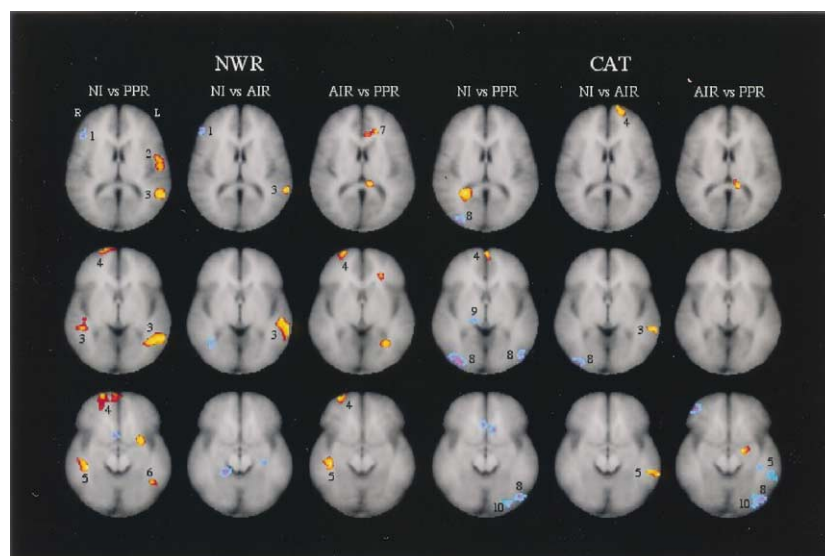


Figure 2. Composite contrast maps directly comparing the brain activation of the three groups during the NWR and CAT tasks. The first three columns contrast the groups during the NWR task; the last three columns contrast the groups during the CAT task. In each column, red-yellow indicates brain regions that were more active ($p = .05$) in the first group compared to the second; blue-purple indicates brain regions more active ($p = .05$) in the second group compared to the first. For example, in the first column labeled NI versus PPR, regions more active in NI compared to PPR during the NWR task are in red-yellow, and areas more active in PPR compared to NI are in blue-purple. The three rows of images from top to bottom correspond to $z = +12, +4, -4$ in Talairach space (Talairach and Tournoux 1988). The legend for regional brain activation is as follows: 1) inferior frontal gyrus, 2) precentral gyrus, 3) superior temporal gyrus and superior temporal sulcus, 4) superior frontal gyrus, 5) middle temporal gyrus, 6) posterior inferior temporal gyrus and anterior middle occipital gyrus, 7) anterior cingulate gyrus, 8) middle occipital gyrus, 9) thalamus, and 10) inferior occipital gyrus.

p-value. It is the proportion of times we would expect to obtain a mean activation as large or larger than the one obtained if the null hypothesis (no difference between tasks) were true. The *p*-value at each voxel ($p < .05$) was then overlaid on the mean anatomic image for display.

CONNECTIVITY METHODS. We employed a method of assessing functional connectivity based on the *seed-voxel* correlation approach (Horwitz et al 1992) extended with the use of inter-regional Partial Least Squares (PLS) (McIntosh et al 1996, 1997). This multivariate analysis examines the correlations of a source region to other brain areas and the differences in these correlations across subject groups. In practice, a source region is chosen for analysis, and activity in this region is correlated with activity in all other brain areas. Based on the extensive literature (see Discussion) relating the left occipitotemporal area as critical in skilled, automatic reading, we selected this region (Talairach coordinates $-55, -36, -5$) as the source region for analysis. Maps of correlations are computed across subjects but separately within each reading group, and thus reflect the amount to which the source region coactivates with every other region, across subjects. For example, a strong correlation of a source occipitotemporal region to inferior frontal gyrus within the NI group would mean that NI subjects who strongly activated the occipitotemporal area would also strongly activate inferior frontal gyrus; other NI subjects who activated the occipitotemporal area less would also activate inferior frontal gyrus less. Correlations such as these imply a functional connection between these sites. Since these correlations represent a distributed system, PLS is then employed to extract the primary components of the correlational pattern. This is accomplished by Singular Value Decomposition of the correlation matrices, producing a small set of multivariate components. These are similar to those obtained from Principal Components Analysis (PCA) in that they combine correlations across the multiple dependent measures. Within each component, loadings to brain voxels are shown as maps and indicate the set of areas that correlate with the source region. Unlike PCA, PLS allows the inclusion of additional categorical variables (e.g., subject group, NI, AIR, PPR), and each component also includes loadings to each group (i.e., how strongly each group reflects that correlational pattern). In this way, PLS can identify functional connectivity patterns that are *common* across all subjects as well as patterns that are *different* across subject groups.

Word Pronunciation Task

In this out-of-magnet task, monosyllabic words (low frequency and high frequency) appeared one at a time on the screen. Subjects were instructed to pronounce each target as quickly as possible while maintaining accuracy. Reaction time and accuracy were recorded for each target.

Results

BRAIN ACTIVATION DURING NWR and CAT. During NWR (pseudoword rhyming), in contrast to NI, both AIR and PPR demonstrated a relative underactivation in posterior neural systems located in the superior temporal and

the occipitotemporal regions (Figure 1, columns 2 and 3; Figure 2, columns 1 and 2). Compared to PPR, AIR activated the right superior frontal and right middle temporal gyri, as well as the left anterior cingulate gyrus (Figure 2, column 3), suggesting that AIR readers, who perform better than do PPR on all reading tasks, have come to rely on compensatory neural systems. These compensatory systems engaged by AIR are in addition to the right inferior frontal gyrus that is activated more in both AIR and PPR than in NI readers (Figure 2, columns 1 and 2). During CAT (reading *real* words) brain activation patterns in the AIR and PPR readers diverged. As they had for NWR, compared to NI, AIR demonstrated relative underactivation in left posterior regions (Figure 1, column 5; Figure 2, column 5). In contrast, during real word reading, PPR subjects activated posterior systems (Figure 1, column 6) and there were no differences between NI and PPR in the temporoparietal area; in the occipitotemporal region, the PPR appeared to demonstrate an *increase* in activation compared to NI (Figure 2, column 4), findings that were both new and unexpected. Thus, despite the significantly better reading performance in NI compared to PPR on every reading task administered, left posterior reading systems were activated during reading real words in both NI and PPR.

FUNCTIONAL CONNECTIVITY. We focused our connectivity analysis on the real-word reading condition (CAT), because it is in this task that the PPR readers displayed unexpected activation of the left occipitotemporal site (Figure 1), and we felt it most critical to further examine the connectivity of this site to other brain regions during real-word reading. Although both the NI and PPR groups activated the left occipitotemporal site, we suppose that the area plays a different functional role in the two groups. Specifically, we hypothesize that in NI readers the occipitotemporal region processes print in a linguistically structured manner and should interact with other areas implicated in orthographic and phonological processing. We further hypothesize that in PPR readers the occipitotemporal area serves as a visually based memory system and should interact with other areas implicated in memory retrieval. Results indicated that NI readers demonstrated connectivity between the left occipitotemporal seed region and the left inferior frontal gyrus, a traditional language region (Figure 3, column 1). In contrast, PPR subjects (Figure 3, column 2) demonstrated functional connectivity between the seed region and right prefrontal areas often associated with working memory and memory retrieval (Fletcher et al 1997; MacLeod et al 1998), a finding consistent with the hypothesis that in the persistently poor readers the occipitotemporal area functions as a component of a memory network. This illustrates a basic distinc-

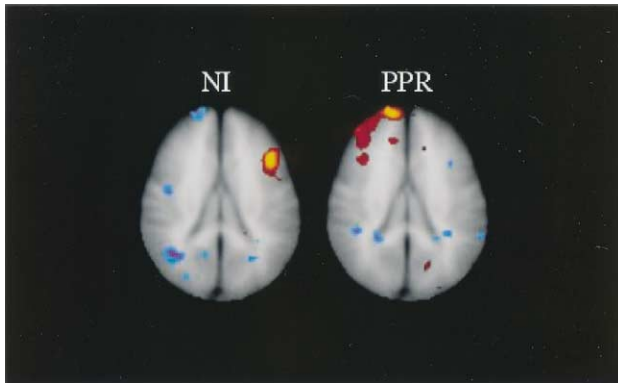


Figure 3. Group connectivity profiles between the seed region in the left occipitotemporal region (Talairach coordinates $-55, -36, -5$) and other brain regions during the CAT (real word) reading task. Red-yellow represent positive loadings and relatively higher connectivity; blue-purple indicates negative loadings and relatively lower connectivity. The images correspond to $z = +24$ in Talairach space; threshold loadings $> \pm .2$. Of primary interest are the second and third components, which strongly differentiated the NI and PPR groups. Component 2 identified a pattern strongly present in the NI group (group loadings NI: .979; AIR: $-.202$; PPR: .003). Strong positive loadings to brain sites (column 1) were seen mainly in Broca's area and additionally in the medial superior frontal gyrus. Component 3 indicated a pattern most strongly present in the PPR group (group loadings NI: $-.079$; AIR: $-.395$; PPR: .916). Positive loadings to brain sites (column 2) were seen in regions of the right middle and inferior frontal gyri, brain regions implicated in attention and memory. Component 1 (not shown) indicated a correlational pattern strongly present in the AIR group (group loadings NI: .186; AIR: .896; PPR: .402). Positive loadings to brain sites were present in right lingual gyrus and the left superior frontal gyrus.

tion between activation analyses and connectivity analyses: greater activation of a region does not necessarily imply greater covariation with other regions, and differential covariation can occur without a concomitant difference in activation level (see Horwitz et al [1999] for a theoretical review; and Grady et al [2001]; McIntosh et al [1997] for empirical examples involving the right prefrontal cortex). In other words, the same activity level within a region can reflect different underlying processing, depending on which other areas the seed region is interacting with (correlated to).

We believe that careful attention must be paid to effects that may arise from differential effort and/or performance levels. We cannot unequivocally disentangle differential effort-based explanations from differential processing-based explanations, because we choose to examine dyslexics while they read, the task in which they inherently show performance differences relative to nonimpaired readers; however, we feel that this is an unlikely explanation for the differential occipital-temporal-prefrontal connectivity for several rea-

sons. First, increased effort or increased time-on-task in the PPR group could in principle explain higher activation of attentional sites; but in general, we did not see higher activation of these prefrontal sites (i.e., the anterior cingulate gyrus) in the PPR group relative to either AIR or NI. Second, this effect is not a simple activation, but an increased *correlation* between two distant regions. While it is easy to envision that increased difficulty might result in generally higher brain activations in a number of sites, it is more difficult to imagine it resulting in increases of distant, regionally specific correlations, especially correlations among sites generally implicated in visual processing (the occipitotemporal region) and memory (right prefrontal cortex) as opposed to attention.

Further support for the hypothesis that in the persistently poor readers the occipitotemporal area functions as a component of a memory network comes from the performance on the out-of-magnet word pronunciation task where word frequency was varied. Both AIR and PPR groups were less accurate than NI readers. For high-frequency words, NI (96% accuracy), AIR (92% accuracy), and PPR (92% accuracy) all performed well; in contrast, for low-frequency words, NI subjects maintained this high degree of accuracy (94%) as did AIR (92%), while PPR subjects identified significantly fewer words (83%). The interaction between reading group and word frequency is significant ($F = 5.52, p < .01$); for PPR (but not AIR or NI) the difference in accuracy between high- and low-frequency words is significant [$F(1,20) = 15.5, p < .001$], suggesting that the PPR readers have difficulty analyzing unfamiliar words and rely more on memory-based rather than analytic word identification strategies.

BEHAVIORAL MEASURES. As young adults (Table 1, Measures as Young Adults), the three groups differed on word reading, pseudoword reading, and on several measures of oral reading, including reading rate, with PPR $<$ AIR $<$ NI. Continuous variables in these and subsequent analyses were analyzed in a one-way analysis of variance (ANOVA) with reading group as the between-subjects factor. Post hoc pairwise comparisons of the three reading groups, summarized in the caption of Table 1, were tested at the Bonferroni-corrected $p < .05$. Woodcock Johnson - Revised reading measures: Letter-Word Identification [$F(2,67) = 37.36, p < .001$]; Word Attack [$F(2,67) = 49.96, p < .001$]. Gray Oral Reading measures: Accuracy [$F(2,66) = 61.83, p < .001$]; Rate [$F(2,66) = 116.89, p < .001$]; Passage [$F(2,66) = 103.01, p < .001$]; and Oral Reading Quotient [$F(2,66) = 41.34, p < .001$]. On two measures, oral reading comprehension and prose literacy, a measure of functional reading ability, NI and AIR were not significantly different from one another but PPR were significantly more impaired than either NI or AIR; Gray

Table 1. Early Influences and Measures as Young Adults

	Group		
	NI (<i>n</i> = 27)	AIR (<i>n</i> = 19)	PPR (<i>n</i> = 24)
Early Influences			
Family SES ^{a,f}			
High	18	6	8
Average	7	6	6
Low	2	7	10
% School Subsidized Meals ^{b,g}	11.2 (13.3)	15.5 (19.5)	28.4 (25.6)
Child			
WISC-R (Wechsler 1981) FSIQ—Grade 1 ^c	116 (9.1)	108 (11.0)	97 (16.1)
Woodcock Johnson Reading (Woodcock and Johnson 1977)—Grade 1 ^a	117 (9.4)	94.0 (11.2)	87.9 (15.1)
Measures as Young Adults			
Age (years)	20.3 (1.0)	19.9 (.9)	19.9 (1.1)
WAIS-R (Wechsler 1981) FSIQ ^d	110 (8.5)	100 (9.9)	91.2 (11.0)
Woodcock-Johnson Revised (Woodcock and Johnson 1989)			
Letter-Word Identification ^d	123 (13.0)	109 (15.0)	95.8 (3.9)
Word Attack ^d	141 (11.4)	122 (16.6)	104 (11.4)
Gray Oral Reading (Wiederholt and Bryant 1992)			
Accuracy ^d	12.2 (3.3)	5.7 (3.2)	3.1 (2.3)
Rate ^d	14.1 (1.2)	9.2 (2.1)	6.7 (2.0)
Passage ^d	13.2 (2.1)	7.6 (2.2)	4.9 (2.0)
Comprehension ^c	10.5 (3.4)	10.2 (2.8)	7.7 (3.4)
Quotient ^d	111 (12.4)	93.2 (12.9)	77.9 (13.7)
Prose Literacy ^{e,h}	341 (28.2)	319 (27.1)	283 (36.8)

Numbers in parentheses are SD.

NI, nonimpaired readers; AIR, accuracy improved (compensated) readers; PPR, persistently poor readers; SES, socioeconomic status; WISC-R, Wechsler Intelligence Scale for Children-Revised; FSIQ, fullscale intelligence quotient; WAIS-R, Wechsler Adult Intelligence Scale-Revised.

^aNI > AIR, AIR = PPR, NI > PPR

^bNI = AIR, AIR = PPR, NI < PPR

^cNI = AIR, AIR > PPR, NI > PPR

^dNI > AIR, AIR > PPR, NI > PPR

^eNI = AIR, AIR = PPR, NI > PPR

^fSES = Socioeconomic status is based on the Hollingshead index (Hollingshead 1976) which ranges from 1 through 5: High (1+2), Average (3), and Low (4+5).

^g% School Subsidized Meals = percentage of students receiving Federal lunch subsidies, a measure frequently used as an index of the aggregate poverty level of the school.

^hProse Literacy = Tests of Applied Literacy Skills (TALS) (Educational ETS 1992) which assesses the same prose literacy skills as measured by the National Adult Literacy Survey.

Oral Reading Comprehension [$F(2,66) = 5.14, p = .008$]; Prose Literacy [$F(2,66) = 21.2, p < .001$]. These data are in agreement with previous studies of adults with childhood histories of reading difficulty (Bruck 1998; Shaywitz et al 1999). As young children (Table 1, Early Influences) both AIR and PPR came from families with lower socioeconomic status (SES) (SES Pearson $\chi^2 [df = 4, n = 70] = 10.82, p = .029$); PPR, but not AIR, attended more disadvantaged schools than NI (percent of students in the participants' schools who received subsidized meals [$F(2,66) = 6.42, p = .003$]). While reading scores at first grade were comparable in AIR and PPR, there were early differences in cognitive ability between the two groups: compared to PPR, AIR as early as first grade demonstrated significantly higher FS IQ (WISC-R FS IQ in Grade 1 [$F(2,67) = 14.6, p < .001$]).

Discussion

These data for rhyming pseudowords (NWR) are consistent with functional brain imaging studies showing

a failure of left hemisphere posterior brain systems to function properly in both adults (Brunswick et al 1999; Helenius et al 1999; Horwitz et al 1998; Paulesu et al 2001; Rumsey et al 1992, 1997; Shaywitz et al 1998; Simos et al 2000) and children (Shaywitz et al 2002; Temple et al 2001) with dyslexia while they perform reading tasks. In contrast, left posterior reading systems were activated during reading *real* words in both NI and PPR. We did not find differences in the insula, as reported by some investigators in children (Corina et al 2001) and in adults (Paulesu et al 1996), though in the NWR task the region of activation in NI readers (Figure 1, column 1) does include the insula; however, on the contrast image between NI and PPR (Figure 2, column 1), this region is not significantly different between groups.

One reasonable explanation for these unexpected findings comes from a consideration of the hypothesis that there are two systems critical in the development of skilled, automatic reading (Dejerine 1891, 1892; Logan 1988, 1997). According to this theory, one system involves word analysis,

operates on individual units of words such as phonemes, and processes relatively slowly; the second system operates on the whole word (word form) and processes very rapidly. Converging evidence from a number of lines of investigation indicates that the word analysis system is localized within the parietotemporal region, while the automatic, rapidly responding system is localized within the occipitotemporal area, functioning as a visual word form area (Cohen et al 2000, 2002; Dehaene et al 2001, 2002; Moore and Price 1999), that appears to respond preferentially to rapidly presented stimuli (Price and Giraud 1998) and is engaged even when the word has not been consciously perceived (Dehaene et al 2001). This region may function for words in an analogous manner to the right hemisphere fusiform face area for expertise (Gauthier 2000; Gauthier et al 2000; Tarr and Gauthier 2000). Our data indicate that both NI and PPR readers rely on the occipitotemporal system for reading real words but engage this system differently. We suppose that NI readers have developed this system through phonologically based word analysis; in contrast, PPR rely more on rote memory for recognizing real words. Support for this position comes, in part, from results of an analysis of functional connectivity. Thus, as seen in Figure 3, results indicate that NI readers demonstrate a connectivity between the left occipitotemporal seed voxel region and the left inferior frontal gyrus, a traditional language region. In contrast, PPR subjects engaged in reading real words demonstrate functional connectivity between the left occipitotemporal seed voxel region and right prefrontal areas often associated with working memory and memory retrieval (Fletcher et al 1997; MacLeod et al 1998), a finding consistent with the hypothesis that in the persistently poor readers the occipitotemporal area functions as a component of a memory network. Further support for this view comes from the word pronunciation task where PPR and NI scored similarly in pronunciation of high-frequency words, but PPR, compared to NI, recognized significantly fewer low-frequency words.

Insight to some of the factors responsible for compensation on the one hand and persistence on the other comes from an examination of the early childhood measures. The two groups of disabled readers (AIR and PPR) began school with comparable reading skills and sharing similar family socioeconomic status but with AIR exhibiting better cognitive ability. These findings suggest that despite similar socioeconomic risk factors for reading disability early in life, the presence of compensatory factors such as stronger cognitive ability allowed the AIR to minimize, in part, the consequences of their phonologic deficit, so that as adults AIR were indistinguishable from NI on a measure of reading comprehension and a measure of prose literacy. These

findings are consonant with a large body of evidence indicating that the impact of dyslexia can be modified by the availability of compensatory resources, for example, semantic knowledge (Snowling et al 2000), use of context (Frith and Snowling 1983; Nation and Snowling 1998), visual memory (Campbell and Butterworth 1985), and verbal ability (Torgesen et al 2001) to compensate for phonologic deficits. In adults, verbal abilities, as measured by verbal IQ, directly predict reading accuracy, with phonologic factors influencing reading indirectly through their effects on verbal IQ (Berninger et al 2001). The current study extends such findings by demonstrating that childhood cognitive ability may be an important influence on the development of reading skills in later childhood and into adult life. Beginning reading is most related to phonologic skills, and within a few years, other language skills, for example semantic knowledge, gain in importance. The current findings suggest that greater cognitive abilities may provide some degree of compensation for a reading difficulty; intuitively this makes sense since a larger vocabulary and better reasoning skills are helpful when a struggling reader is trying to decipher unknown words. If the word is in his spoken language vocabulary, the beginning reader may recognize the word even if he can only partially sound it out. Strong reasoning abilities also help this reader to use the context around an unknown word to figure out its meaning. The imaging findings noted earlier which demonstrate a greater number of ancillary systems in AIR compared to PPR may represent the neural correlates of this compensation.

These findings have important educational implications and are of special relevance for teaching children to read. Consistent with our knowledge of the components of reading, children need to be able to sound out words to decode them accurately, and then, they need to know the meaning of the word, to help decode and comprehend the printed message. Both the sounds and the meanings of words must be taught. These findings suggest that it may be beneficial to provide early interventions aimed at stimulating both phonologic and verbal abilities in children at risk for reading difficulties associated with disadvantage.

Finally, for the first time, results from functional brain imaging studies distinguish two potential types of reading disability. These are consistent with Olson's suggestion of two possible etiologies for childhood reading disability: a primarily genetic type with IQ scores over 100 and a more environmentally influenced type with IQs below 100 (Olson 1999; Olson et al 1999; Wadsworth et al 2000). Though clearly, genetic and environmental factors play a role in reading in all children, it is intriguing to speculate that the AIR

subjects may represent a predominantly genetic type, while the PPR group, with significantly lower IQ and a trend to attend more disadvantaged schools, may represent a more environmentally influenced type of dyslexic reader. We speculate that in young adults the neural system differences between these groups may not have been recognized before because previous functional imaging studies have generally focused on the compensated dyslexics who, with appropriate accommodations, are more successful academically and are able to enter university (Brunswick et al 1999; Paulesu et al 2001), while the environmentally influenced poor readers rarely attend university and may not readily come to the attention of investigators.

This work was supported by grants from the National Institute of Child Health and Human Development (PO1 HD 21888 and P50 HD25802). The authors thank Carmel Lepore, Hedy Sarofin, and Terry Hickey for their invaluable help in imaging subjects. The authors thank also Jun Ren Lee and Cheryl Lacadie for their help with data analysis.

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