

PAPER

Brain–behavior relationships in reading acquisition are modulated by socioeconomic factors

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Abstract

Functional neuroimaging may provide insights into the achievement gap in reading skill commonly observed across socioeconomic status (SES). Brain activation during reading tasks is known to be associated with individual differences in children's phonological language skills. By selecting children of equivalent phonological skill, yet diverse socioeconomic backgrounds, we use functional magnetic resonance imaging (fMRI) to demonstrate that a child's experience, as operationalized by SES, can systematically modulate the relationship between phonological language skills and reading-related brain activity in left fusiform and perisylvian regions. Specifically, at lower socioeconomic levels, individual differences in skill result in large differences in brain activation. In contrast, as SES increases, this relationship between phonological language skill and activation is attenuated. Socioeconomic background factors are thus found to modulate brain–behavior relationships in reading, indicating that cognitive, social, and neurobiological influences on reading development are fundamentally intertwined.

Introduction

Learning to read is one of the major milestones of child development. Brain imaging can provide insights into the neurobiological basis of this cognitive transition, and can now be used to understand the neural bases of individual differences in children's literacy acquisition.

Socioeconomic status (SES), typically indexed by parental education, occupation, and income (Entwisle & Astone, 1994), is a robust predictor of children's reading achievement, with higher SES associated with higher levels of reading skill (Bowey, 1995; Hecht, Burgess, Torgesen, Wagner & Rashotte, 2000; Raz & Bryant, 1990). Evidence has suggested that SES is predictive of multiple components of reading skill and development, including decoding, print knowledge, and comprehension (Adams, 1990; Bowey, 1995; Dickinson & Snow, 1987; Hecht *et al.*, 2000; Lonigan, Burgess, Anthony & Barker, 1998; Raz & Bryant, 1990).

Many elements potentially underlie this SES gap in reading achievement, including differences in schooling (Barnett, 1998; Ramey & Ramey, 1998), physical health (Hawley & Disney, 1992; Klein, Hack & Breslau, 1989;

McCormick, 1989; Needleman, Schell, Bellinger, Leviton & Allred, 1990), emotional support, parenting practices (Andersson, Sommerfelt, Sonnander & Ahlsten, 1996; Korenman, Miller & Sjaastad, 1995; McLoyd, 1990), and stress (Lupien, Gillin & Hauger, 1999). One factor worth particular mention is the SES gradient in reading-related experiences, such as the degree of print exposure in the home, and the quality of early schooling (Adams, 1990; R.H. Bradley, Corwyn, Pipes McAdoo & Garcia Coll, 2001; Hecht *et al.*, 2000; Raz & Bryant, 1990; Whitehurst, 1997). Across ethnic groups, children from higher SES backgrounds are far more likely to own books and to have greater access to resources such as museums or libraries (R.H. Bradley, Corwyn, Pipes McAdoo *et al.*, 2001), and a strong relation between cognitively stimulating experiences and academic achievement has been well documented (R.H. Bradley & Corwyn, 2002; R.H. Bradley, Corwyn, Burchinal, Pipes McAdoo & Garcia Coll, 2001; Brooks-Gunn & Duncan, 1997; McLoyd, 1998).

A cognitive skill known as phonological awareness (PA), or the ability to explicitly represent and manipulate the sounds of language, also strongly predicts reading achievement (L. Bradley & Bryant, 1983; Share, Jorm,

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MacLean & Mathews, 1984; Wagner & Torgesen, 1987). Reading requires the ability to map between the distinct sounds in words and distinct letter combinations; PA is therefore an important cognitive precursor to reading ability, with individual differences in this skill tightly related to children's variable progress in learning to read. Furthermore, differences in children's PA strongly predict differences in reading-related brain activity (B.A. Shaywitz, S.E. Shaywitz, Pugh, Mencl, Fulbright, Skudlarski, Constable, Marchione, Fletcher, Lyon & Gore, 2002; Turkeltaub, Gareau, Flowers, Zeffiro & Eden, 2003), and such differences in brain activation are themselves predictive of a child's reading achievement level (B.A. Shaywitz *et al.*, 2002; Simos, Fletcher, Bergman, Breier, Foorman, Casillo, Davis, Fitzgerald & Papanicolaou, 2002; Temple, Poldrack, Salidis, Deutsch, Talla, Merzenich & Gabrieli, 2001; Turkeltaub *et al.*, 2003). Brain activation may thus be a central mediating factor between a cognitive precursor skill like PA and ultimate reading achievement. But how is the relationship between cognitive skill and reading-related brain activity influenced by a child's background and experiences?

Despite abundant work showing that SES and PA are each associated with reading achievement, little is known about how cognitive precursors of reading ability like PA interact with the background and experiences that a child brings to the classroom. To some extent, this is due to the fact that SES, PA and reading achievement are typically inter-correlated, making it difficult to tease apart cognitive and sociological effects. By specifically selecting children from diverse socioeconomic backgrounds who nonetheless showed an equivalent range of PA abilities, we recently have been able to demonstrate that the effect of phonological precursor skills on reading achievement is not constant across SES levels, but rather that PA and SES interact in a multiplicative fashion (Noble, Farah & McCandliss, 2006). Specifically, at higher PA levels, children were generally reading at an above-average level, regardless of background. However, at lower PA levels, a disparity began to emerge such that most children from higher socioeconomic backgrounds were still reading relatively well, whereas many children from lower socioeconomic backgrounds were struggling. This interaction held even when verbal IQ was taken into account. Thus, the relationship between PA and reading achievement is modulated by SES, such that this relationship is exaggerated under low-resource conditions but attenuated under high-resource conditions.

One possible interpretation of these results is that greater access to resources associated with a higher SES environment may buffer reading skills among children with lower PA. To understand the mechanism by which cognitive and sociological factors act in a multiplicative

fashion, however, it is necessary to examine the patterns of functional neural activity that occur while children read.

Converging evidence suggests that the left occipito-temporal region (Brunswick, McCrory, Price, Frith & Frith, 1999; Fiez, Balota, Raichle & Petersen, 1999; McCandliss, Cohen & Dehaene, 2003; Paulesu, Demonet, Fazio, McCrory, Chanoine, Brunswick, Cappa, Cossu, Habib, Frith & Frith, 2001; Price, Wise & Frackowiak, 1996; Rumsey, Nace, Donohue, Wise, Maisog & Andreason, 1997; B.A. Shaywitz, Shaywitz, Pugh, Mencl, Fulbright, Skudlarski, Constable, Marchione, Fletcher, Lyon & Gore, 2002), including the fusiform gyrus, and the left perisylvian region (Eckert, Lombardino & Leonard, 2001; Galaburda, Rosen, Aboitiz & Geschwind, 1985; Klingberg, Hedehus, Temple, Salz, Gabrieli, Moseley & Poldrack, 2000; Price, Moore, Humphreys & Wise, 1997; Rumsey, Andreason, Zametkin, Aquino & King, 1992; Rumsey, Horwitz, Donohue, Nace, Maisog & Andreason, 1997; B.A. Shaywitz *et al.*, 2002; S.E. Shaywitz, Sahywitz, Pugh, Fulbright, Constable, Mencl, Shenkweiler, Liberman, Skudlarski, Fletcher, Katz, Marchione, Lacadie, Gatenby & Gore, 1998; Simos *et al.*, 2002; Temple *et al.*, 2001; Turkeltaub *et al.*, 2003), including the left superior and middle temporal gyri, support the typical development of reading (Brunswick *et al.*, 1999; Fiez *et al.*, 1999; Price *et al.*, 1997; Price *et al.*, 1996; Rumsey, Horwitz *et al.*, 1997; B.A. Shaywitz *et al.*, 2002; S.E. Shaywitz *et al.*, 1998) and exhibit dysfunction in cases of reading impairment (Binder & Mohr, 1992; Brunswick *et al.*, 1999; Eckert *et al.*, 2001; Galaburda *et al.*, 1985; Klingberg *et al.*, 2000; Paulesu *et al.*, 2001; Rumsey *et al.*, 1992; Rumsey, Horwitz *et al.*, 1997; Rumsey, Nace *et al.*, 1997; B.A. Shaywitz *et al.*, 2002; S.E. Shaywitz *et al.*, 1998). These findings have been demonstrated in both anatomical (Binder & Mohr, 1992; Eckert *et al.*, 2001; Galaburda *et al.*, 1985; Klingberg *et al.*, 2000) and functional (Brunswick *et al.*, 1999; Price *et al.*, 1996; Rumsey *et al.*, 1992; Rumsey, Horwitz *et al.*, 1997; S.E. Shaywitz *et al.*, 1998) studies, and in both adults (Brunswick *et al.*, 1999; Paulesu *et al.*, 2001; Price *et al.*, 1996; Rumsey, Nace *et al.*, 1997) and children (B.A. Shaywitz *et al.*, 2002; Simos *et al.*, 2002; Temple *et al.*, 2001; Turkeltaub *et al.*, 2003). The left occipito-temporal region supports the development of visual expertise allowing skilled readers to rapidly combine the letters of a word into an integrated visual percept (Brunswick *et al.*, 1999; Fiez *et al.*, 1999; McCandliss *et al.*, 2003; Price & Devlin, 2004; Price *et al.*, 1996), while the left perisylvian region is involved in phonological processing in normal readers (Price *et al.*, 1997; Rumsey, Horwitz *et al.*, 1997; B.A. Shaywitz *et al.*, 2002; S.E. Shaywitz *et al.*, 1998; Temple *et al.*, 2001). Importantly, brain-behavior relationships have been demonstrated in these regions, such that a child's

phonological skill level is positively predictive of the degree of activation observed in these regions while the child performs a reading task in the scanner (B.A. Shaywitz *et al.*, 2002; Turkeltaub *et al.*, 2003). Although this does not constitute an exhaustive list of regions for which evidence exists for involvement in reading-related processes, the regions described represent those that have shown the greatest converging evidence implicated in reading impairment (Noble & McCandliss, 2005).

Although the neural mechanisms behind reading development have been well studied, the degree to which socioeconomic factors may play a role has been left largely unexplained. One study has suggested that perisylvian neuroanatomy and SES each account for unique effects on phonology and reading (Eckert *et al.*, 2001). In that study, however, SES and PA were largely confounded, in that lower SES children were more likely to exhibit lower PA. Explicitly investigating the role of SES in the neural basis of reading requires the recruitment of a socioeconomically diverse population with similar cognitive abilities.

We hypothesize that SES systematically influences the relationship between phonological skill and brain activity in regions involved in reading. Specifically, we predict that the strength of the association between PA and brain activity will be increased in an environment with low exposure to literacy-based (and other) resources. Conversely, in an environment with plentiful access to resources, the influence of PA on brain activity may, to an extent, be reduced. This hypothesis thus predicts a statistical interaction between PA and SES on reading-related activity in left occipito-temporal and perisylvian regions. Children from the lower end of the SES continuum are predicted to show a strong positive association between PA and activity in these regions, whereas, as SES increases, children with similar PA are predicted to demonstrate a reduced association between PA and activity in these areas.

To test this hypothesis, we examined fMRI responses during a pseudoword reading task across a group of children who represented diverse socioeconomic backgrounds, yet who showed an equivalent range of PA skills spanning from impaired to normal levels. Here we provide evidence that a child's experience, as operationalized by SES, can systematically modulate brain-behavior relationships in reading.

Method

Subjects

We recruited healthy, right-handed, 1st- to 3rd-grade native English-speaking children from socioeconomically diverse

Table 1 Demographics of sample ($n = 38$)

Mean age (range)	7:11 (6:9 to 9:7)
Gender	21 Females, 17 Males
Race	
African-American	11
Latino	5
Asian/Pacific Islander	1
White	14
Mixed/Other	7
Mean parental education (range)	14 (9–19)
Mean parental Hollingshead Occupation Status (range)	5 (1–9)
Mean family income-to-needs ratio (range)	2.93 (0.3–11.4)

New York City elementary schools as part of a larger intervention study for poor readers. (All procedures in the present study occurred prior to intervention in qualifying children.) Socioeconomically diverse schools were targeted using public records of percentage of children receiving free lunch. By explicitly targeting parents of children with reading difficulties at these schools, we had the goal of recruiting children with below-average phonological and reading skills, but who came from a range of socioeconomic backgrounds, such that SES and phonological skill would be uncorrelated. Children with receptive vocabulary standard scores < 75 were excluded from participation, regardless of reading score. The Weill Medical College of Cornell University Institutional Review Board approved all experimental procedures, and informed consent was obtained from each participant and a parent or legal guardian.

Seventy-four children were invited to attempt the scan. All children received practice in an MRI simulator prior to the acquisition of functional data, to maximize accuracy and minimize head motion. Inclusionary criteria for analysis included minimal head motion and good task performance as described below, as well as the absence of scanner-related image artifact. Thirty-eight subjects (21 girls, 17 boys) met the inclusionary criteria, and were included in the final analysis (see Table 1). The mean age of these subjects was 7 years, 11 months (range 6:9 to 9:7). Eleven children were identified by parental report as African-American; five as Latino; one as Asian, 14 as White, and seven as mixed or other. Three children were medicated for ADHD at the time of the scan; no other children were taking psychotropic medications of any kind. Four children had been diagnosed with a learning disability. No child had suffered a head injury resulting in loss of consciousness, and no child had a diagnosis of a neurological disorder. Eight children came from single-parent families.

Behavioral testing

All subjects completed a battery of standardized tests of reading, receptive vocabulary, and phonological processing as part of a larger intervention study. Performance on a subset of these tests was analyzed for the present study. To measure phonological awareness, the 'Blending Words' and 'Elision' subtests from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen & Rashotte, 1999) were administered. 'Blending Words' measures the child's ability to combine sounds to form words. The child listens to a series of tape-recorded sounds and is asked to put the sounds together to make a whole word. 'Elision' measures the child's ability to say a word without saying a specific sound. For example, the child is told to say *bold*, and to then say *bold* without saying /b/, such that the correct response is *old*. Items on both subtests progress in difficulty and each test is stopped when the child answers three items in a row incorrectly. Scores for the two subtests were standardized based on age and averaged to formulate a phonological awareness composite for each child.

To obtain a standardized reading measure, the 'Word Attack' subtest of the Woodcock-Johnson III Tests of Achievement (Woodcock, McGrew & Mather, 2001) was administered. In this test, the child reads unfamiliar nonwords, which must be decoded by letter-sound correspondence rules. Items progress in difficulty and the test is terminated when ceiling is reached. Scores are standardized based on grade level.

Receptive vocabulary was measured using the Peabody Picture Vocabulary Test, 3rd edition (PPVT-III). The child hears a word on each trial, and must select the corresponding picture that best depicts the word from among four choices. Scores are standardized based on age.

Parent questionnaire

Parents were administered a 5-minute questionnaire involving questions pertaining to parental education, occupation, and income levels, as well as to the child's medical and psychiatric history. Parental education was defined as the average education of any parents, step-parents, or guardians in the home (mean 14 years; range 9–19). Parental occupation was defined as the highest occupational score of any parent, step-parent, or guardian in the home, according to the 9-point Hollingshead Index Occupational Status Scale (mean 5, range 1–9) (Bornstein & Bradley, 2003). The income-to-needs ratio, defined as the total family income divided by the official poverty threshold for a family of that size, was calculated for each family, such that a family with an income-to-

needs ratio of 1 is living at the poverty line (McLoyd, 1998). The average income-to-needs ratio was 2.93 (range 0.3–11.4). A composite SES score was then calculated for each child from a linear combination of parental education, occupation, and income-to-needs derived from a factor analysis loading score on a single principal component (mean 0, SD 0.75), which had previously been shown to account for 73.5% of the variance in the three SES variables, using a sample of 150 New York children of similar demographics to the subjects studied here (Noble *et al.*, 2006).

Functional imaging procedure and analysis

Subjects were presented with visual letter strings, four letters in length, using equipment by IFIS Technologies to project the image onto a screen. To ensure attention to the stimuli, subjects were engaged in a letter string one-back task, in which they were instructed to press a button with their right index finger each time they saw the same four letters on the screen two times in a row. The two sets of stimuli relevant to the current study consisted of epochs of pronounceable nonwords (pseudowords; e.g. *blif*) and epochs of crosshair fixation. In addition, a third type of stimulus was included for the purposes of another study, consisting of epochs of non-pronounceable letter strings (consonant strings; e.g. *strf*). Each run consisted of six 38-second epochs, with two epochs each of pseudowords, consonant strings, and fixation. The order of epochs was counterbalanced across six runs. Stimuli were presented for 1000 ms, with a 1000-ms interstimulus interval (ISI), such that 76 letter string stimuli were presented per run (19 per epoch). In each run, there were 16 repetitions (i.e. targets; four per epoch). Pseudowords were generated from onset-rime substitution of 100 high frequency content words from children's books (Zeno, Ivens, Millard & Duvvuri, 1995), and consonant strings were generated from vowel substitution (Compton, Grossenbacher, Posner & Tucker, 1991). Data presented here are restricted to contrasts of pseudoword trials vs. fixation baseline, as consonant strings were presented in the context of a separate study, with the aim of isolating phonological processing during reading for a subset of children who met performance criteria for both pseudowords and consonant strings. Furthermore, in-scanner task performance of the two types of letter strings was quite different for the subjects included in the present study ($t(37) = -4.7$; $p < .0001$), rendering a direct contrast of the two conditions somewhat less interpretable.

Data were acquired on a 1.5 Tesla GE scanner using a T2* echoplanar imaging (EPI) sequence (TR = 2s; TE = 40 ms; flip angle = 90°; field of view = 20 cm; 64 × 64

matrix; 24 contiguous straight axial 4-mm slices). Within each run, a total of 119 volumes were acquired for each subject over 238 seconds. Five volumes (a total of 10 s) acquired at the beginning of each run were subsequently discarded to allow for the signal to reach steady state. Anatomical images were also obtained using T1-weighted 3D SPGR sequence. Head motion was minimized using electrostatic headphones, foam padding and an elastic headband.

Imaging data were analyzed using SPM2 (Wellcome Department of Imaging Neuroscience, University of London, London, UK). Head motion in the three translational directions and three rotational axes was first investigated for all runs acquired for each subject. Any run with more than 4 mm or 4 degrees movement in any direction was excluded. Accuracy of performance on the in-scanner task was measured by *d*-prime, in order to incorporate both hit rate and false alarms. Any run with a *d*-prime of less than 1 was excluded. Using these motion and accuracy criteria, we identified and analyzed the two runs for each of 38 subjects with the greatest accuracy and lowest motion. In-scanner task accuracy was quite high, with a mean *d*-prime of 2.5 (SD 0.93). Bivariate correlations revealed that there was no significant correlation between *d*-prime and Word Attack, indicating that task accuracy was not confounded with decoding ability. Because a small but significant correlation between PA and accuracy of task performance was observed, task accuracy is covaried in all analyses that examine the association between brain activity and PA.

The raw data from each subject's two best runs were subjected to motion correction via Gauss-Newton optimization (Ashburner & Friston, 2003). The average maximum motion in these runs was 1.56 mm (SD 0.96 mm), with the average motion per acquisition 0.052 mm (SD 0.032). Additional preprocessing included reorientation of the SPGR to the AC-PC line, which was then applied to EPI images to optimize normalization, followed by coregistration of functional and anatomical images. Images were spatially normalized to the standardized T2 template of the Montreal Neurological Institute (MNI). Images were spatially smoothed using a Gaussian filter (FWHM 8 mm).

Individual subject data were first analyzed using a fixed-effects model in which data were scaled to the session-specific grand mean and were high-pass filtered for low-frequency noise components at 1 cycle/128 seconds. Individualized orthogonal stimulus-onset vectors of pseudowords, consonants, and responses were created for each subject's two best runs. Condition-specific effects at each voxel were then estimated according to the general linear model, using a single regressor of interest modeling the pseudoword time-series convolved with

the canonical hemodynamic response function (HRF). One contrast image per subject was then passed to the second-level random effects model for group analyses. To account for any possible effects of different runs used, all random effects correlation analyses were analyzed including regressors for run (indicating which two runs of data were used for a particular child).

A random effects analysis of task-related activity was undertaken to examine the neural regions engaged in the task across the group. A statistical parametric map of activity associated with the presentation of pseudoword stimuli vs. the implicit baseline of fixation was produced, using an alpha level of 0.0001 (uncorrected), with a minimum cluster size of 5 voxels.

To constrain our hypotheses, we next conducted an analysis of *a priori* regions of interest (ROIs) based on the neuroimaging literature of reading impairment, enabling us to test regions previously shown to be specifically involved in differences between skilled readers and reading impaired individuals. As reviewed above, converging evidence supports the involvement of the left perisylvian and left occipitotemporal regions in reading development and impairment. Other regions, such as the left inferior frontal gyrus, have proven more controversial, with some studies showing a relative overactivation in impaired readers (S.E. Shaywitz *et al.*, 1998), other studies showing a relative underactivation in the same comparison (Georgiewa, Rzanny, Gaser, Gerhard, Vieweg, Freesmeyer, Mentzel, Kaiser & Banz, 2002; B.A. Shaywitz *et al.*, 2002), and still other studies failing to find a difference in this region (Paulesu *et al.*, 2001). We therefore chose to limit our *a priori* investigation to the left perisylvian and left occipitotemporal regions.

Specific regions of interest were defined following a meta-analysis of 35 neuroimaging studies of reading in adults (Jobard, Crivello & Tzourio-Mazoyer, 2003). (Note that adult reading activation may not necessarily be the best predictor of child data; however, no such meta-analyses are at present available for pediatric populations.) Based on this report, we restricted our *a priori* analyses to 10-mm radius spheres around three points found in the following locations: the left superior temporal gyrus (MNI coordinates -53, -13, 0); the left middle temporal gyrus (MNI coordinates -63, -30, 4); and the left fusiform gyrus (MNI coordinates -44, -58, -15). Each ROI was interrogated to extract a parameter estimate of activity associated with the pseudoword condition for each subject, using the random effects model (including regressors for run). Within each ROI, a principal components analysis was performed on the random effects parameter estimates (e.g. beta values) of all voxels within the region. Each subject's loading score on the first principal component of the signal was

then extracted, providing a single estimate of activation for each ROI for each subject. This component accounted for 68%, 67%, and 72% of the variance of the activity in the voxels identified by the left superior temporal, left middle temporal, and left fusiform ROIs, respectively. The predictive power of PA, SES and the PA \times SES interaction was then explored by interrogating the activity in each ROI, after covarying task accuracy and age.

Finally, to probe whether interactions were present in other brain regions as well, a voxel-wise analysis of activity was conducted using a liberal statistical threshold ($p < .005$ uncorrected; minimum cluster size of 5 voxels). A random effects multiple regression analysis was conducted in which PA, SES, and the PA \times SES interaction were entered as covariates of interest, and task accuracy and run numbers used were entered as covariates of no interest (i.e. their effects were regressed out). We then masked the resultant output for voxels that were significant for the interaction term, revealing clusters that were both significant for the whole model and in which the interaction exceeded the statistical threshold. All interactions remained significant when covarying age.

Results

Behavioral results

Results confirmed a successful strategy of recruiting socioeconomically diverse subjects who exhibited a broad, overlapping range of below-average phonological abilities. Subjects displayed a wide range of phonological abilities, with a mean composite score of 7.9 (SD 1.79), representing approximately $\frac{2}{3}$ of a standard deviation below the national average (see Table 2 for a breakdown of scores by grade level). Subjects were also socioeconomically diverse, with a mean parental education level of 14 years (range 9–19). Yet, in line with our recruitment strategy, SES was not correlated with PA in this sample (see Table 3), enabling us to directly examine the relationship between PA and brain activity across SES.

Subjects were generally below average readers, with a mean Word Attack score of 91.6 (SD 10.8), again representing approximately $\frac{2}{3}$ of a standard deviation below the national average. Mean receptive vocabulary was within the average range (mean 97.6, SD 14.0). SES was not correlated with standardized reading ability, receptive vocabulary, or accuracy on the imaging task (see Table 3), indicating that any associations between SES and brain activity are not confounded with these measures.

fMRI results: pseudoword reading group effects

The blood-oxygen level dependent (BOLD) response associated with the presentation of pseudoword stimuli in contrast to baseline fixation was examined. Across the entire group, prominent activations to the pseudoword condition relative to fixation were seen in bilateral visual areas extending from the inferior occipital gyrus into the middle occipital and occipito-temporal regions; bilateral inferior frontal, middle frontal, and precentral activations (greater on the left); and activation in the left insula (see Table 4).

Region of interest analyses: PA \times SES interaction in left fusiform

To quantify the extent to which behavioral and socioeconomic factors were associated with activation in established occipito-temporal and perisylvian cortical regions involved in reading, functional regions of interest

Table 2 Means and standard deviations of phonological awareness, word attack, and SES by grade

Grade	Phonological awareness		Word attack		SES index	
	Mean	SD	Mean	SD	Mean	SD
1	8.3	1.6	87	7	-0.5	1.1
2	7.7	1.8	90	11	0.1	0.76
3	8.4	1.9	98	9	-0.1	0.6

Table 3 Correlations between accuracy, decoding, PA, SES, and receptive vocabulary

	Task accuracy (d-prime)	Decoding (Word attack)	Phonological awareness (CTOPP composite)	SES Index (Composite of education, occupation, income)	Receptive vocabulary (PPVT)
Task accuracy	–	0.24 (<i>ns</i>)	0.36 ($p < .029$)	0.004 (<i>ns</i>)	0.15 (<i>ns</i>)
Decoding		–	0.47 ($p < .001$)	0.06 (<i>ns</i>)	0.573 ($p < .0001$)
PA composite			–	0.07 (<i>ns</i>)	0.53 ($p < .001$)
SES composite				–	0.24 (<i>ns</i>)
Receptive Vocabulary					–

Table 4 Activations to pseudowords vs. fixation baseline

Region		Coordinates						<i>p</i> (corrected)			
MNI	Talairach	MNI (x,y,z)			Talairach (x,y,z)			Z	Family-wise error	False detection rate	Cluster size (voxels)
R IOG	R IOG	46	-82	-12	46	-80	-6	6.06	0.000	0.000	557
R ITG	R Sub-Gyral	44	-64	-8	44	-62	-4	5.11	0.004	0.000	
R MOG	R IOG	32	-94	-10	32	-91	-4	4.44	0.063	0.001	
L IOG	L MOG	-46	-72	-14	-46	-70	-8	5.54	0.001	0.000	260
L IOG	L IOG	-32	-90	-10	-32	-88	-4	4.25	0.125	0.002	
L PCG	L PCG	-52	-2	38	-51	0	35	5.06	0.005	0.000	
L IFG	L MFG	-42	12	30	-42	13	27	4.89	0.011	0.001	632
L IFG	L MFG	-50	16	32	-50	17	29	4.62	0.031	0.001	
L insula	L Insula	-30	18	4	-30	18	3	4.65	0.029	0.001	
R AG	R SubGyral	30	-56	42	30	-52	41	4.6	0.034	0.001	49
L CB	L CB	0	-56	-20	0	-55	-14	4.47	0.057	0.001	
R MFG	R MFG	42	36	30	42	36	26	4.32	0.096	0.002	
L ITG	L FG	-46	-52	-16	-46	-51	-11	4.04	0.243	0.003	12
L Cing.	L Cing.	-6	16	42	-6	17	38	4.04	0.245	0.003	
R IFG	R IFG	40	2	26	40	3	24	3.96	0.305	0.004	
R PCG	R IFG	46	8	30	46	9	27	3.83	0.42	0.005	33

Note: Peak activations are in bold. Subpeaks more than 8 mm from the peak are in regular font. IOG = Inferior Occipital Gyrus; ITG = Inferior Temporal Gyrus; MOG = Middle Occipital Gyrus; PCG = Precentral Gyrus; IFG = Inferior Frontal Gyrus; AG = angular gyrus; CB = cerebellum; Cing = Cingulate; MFG = Middle Frontal Gyrus; FG = Fusiform Gyrus.

(ROIs) were specified in an *a priori* fashion on the basis of a meta-analytic study (Jobard *et al.*, 2003).

Associations with brain activity in each ROI were examined. In the left fusiform region, a significant PA × SES interaction was observed (Beta = $-.479$; $p < .007$). To insure that this interaction was not driven by a small number of overly influential points, we then re-analyzed the data, eliminating points that wielded an undue influence on the interaction term as measured by the difference in the standardized beta coefficient when deleting the case (Pedhazur, 1997). The interaction retained significance (Beta = $-.549$; $p < .006$; see Table 5). In the left superior temporal gyrus (STG), a borderline significant effect of age (Beta = $-.313$; $p < .074$) and a significant effect of task accuracy (Beta = $.367$; $p < .044$) were observed. When excluding influential points, significant effects of both age (Beta = $-.341$; $p < .034$) and task accuracy (Beta = $.588$; $p < .001$) were observed, as well as a trend for a PA × SES interaction (Beta = $-.293$; $p < .107$). Finally, in the left middle temporal gyrus (MTG), a significant effect of age was observed (Beta = $-.438$; $p < .011$), as well as a borderline effect of task accuracy (Beta = $.279$; $p < .106$). Once again, similar values were found when excluding influential points (Beta = $-.371$; $p < .039$; and Beta = $.292$; $p < .09$ for age and accuracy, respectively).

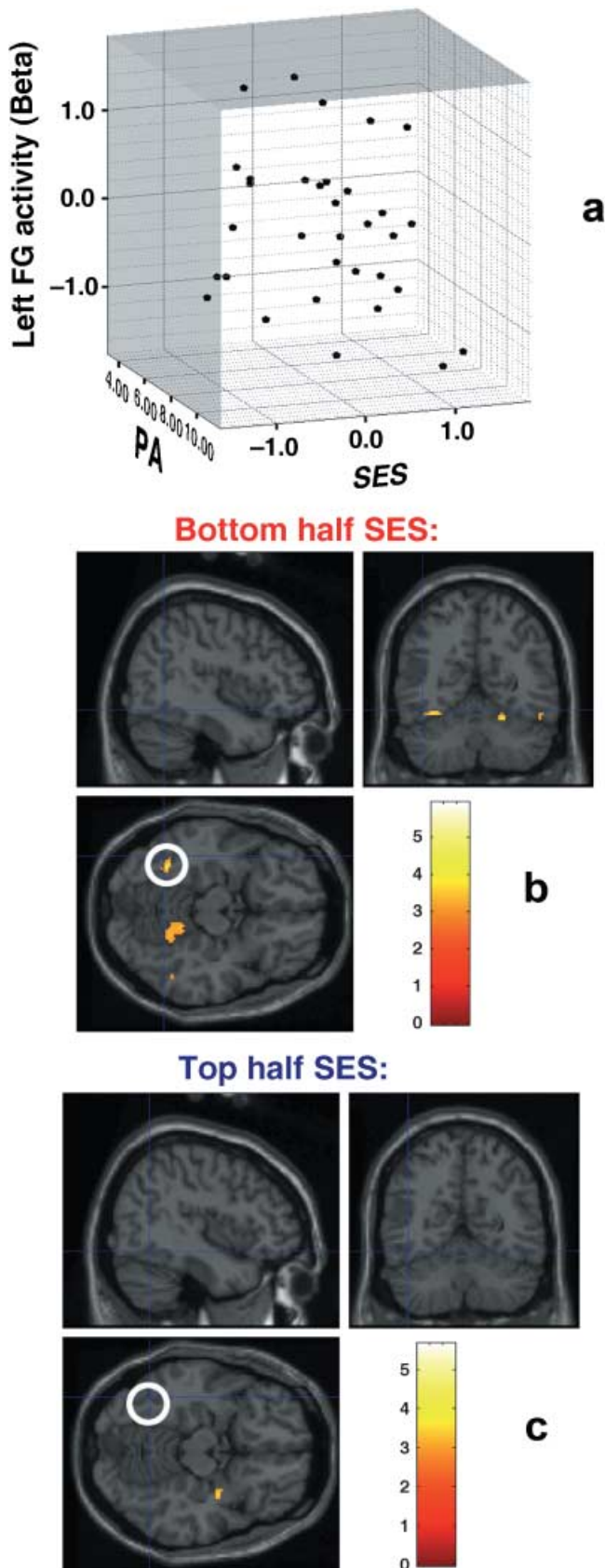
Figure 1 illustrates the nature of this interaction between two continuous variables in the left fusiform gyrus. (Please see online supplementary material to view a spinning 3D figure.) At similar low PA levels, higher

Table 5 Multiple regressions in a priori regions of interest

Region of interest	Model	R ²	B	Standard error of B	Beta	<i>p</i>
Left fusiform	Age	0.318	-0.012	0.019	-0.103	0.544
	Accuracy		0.176	0.161	0.194	0.285
	PA		0.079	0.095	0.154	0.412
	SES		-0.422	0.206	-0.345	0.051
	PA × SES		-0.501	0.168	-0.549	0.006
Left STG	Age	0.450	-0.055	0.024	-0.341	0.034
	Accuracy		0.641	0.174	0.588	0.001
	PA		-0.104	0.101	-0.174	0.315
	SES		-0.106	0.228	-0.073	0.646
	PA × SES		-0.299	0.179	-0.293	0.107
Left MTG	Age	0.287	-0.055	0.025	-0.371	0.039
	Accuracy		0.366	0.209	0.292	0.090
	PA		0.124	0.114	0.182	0.286
	SES		0.005	0.236	0.004	0.982
	PA × SES		-0.087	0.178	-0.085	0.629

Note: Several data points in each region of interest (6 in STG, 1 in MTG, and 5 in fusiform) wielded undue influence on the interaction term as measured by the difference in the standardized beta coefficient when deleting the case (Pedhazur, 1997), and were excluded. The presence or absence of these influential points did not categorically change the results, and following their exclusion, all results presented retained significance. All statistics represent analyses with overly influential points excluded.

SES children are more likely to show an increased response in the left fusiform region, whereas lower SES children are not. This shows that SES can systematically influence brain-behavior relationships: children who exhibit below-average phonological skill in the context of a lower SES environment show a strong relationship between



PA and fusiform activity, whereas this relationship is attenuated among children who exhibit similar phonological skills in the context of a higher SES environment.

Voxel-wise analyses: PA \times SES interactions in left fusiform and bilateral perisylvian regions

A voxel-wise multiple regression analysis was conducted, in which all voxels were queried for the presence of the predicted PA \times SES interaction at an alpha-level of $p < .005$ (uncorrected), thus allowing us to assess the specificity of the above findings by assessing activity in regions that fell outside the *a priori* regions of interest. Table 6 lists regions that demonstrated such interactions. A large cluster is noted in the left fusiform gyrus, extending into the left inferior temporal gyrus, with a peak 10-mm medial to the *a priori* region of interest. In addition, a smaller cluster with a peak in the left Heschl's gyrus is located quite close to the left STG ROI.

Figure 2 illustrates these differences in the left fusiform and bilateral superior temporal gyri. Among lower SES children, a clear positive correlation is seen between PA and activity in the left fusiform region. No such correlation is seen among higher SES children. Similarly, although all children exhibit a positive correlation between PA and left perisylvian activity extending into the superior temporal gyrus, the size of the region exhibiting this correlation is much larger in lower SES children. In contrast, higher SES children exhibit a correlation with PA in a larger area of the right superior temporal gyrus than is seen in lower SES children.

Figure 1 Relationship between activity in left fusiform ROI (Centered at MNI coordinates $-44, -58, -15$) and Phonological Awareness across SES. Scatter plot (a) depicts the partial correlation of PA and left fusiform activity across SES, controlling for age, task accuracy, and runs used. A significant PA \times SES interaction was found ($p < .006$), such that PA is more strongly associated with left fusiform activation at lower SES levels, whereas this association is attenuated as SES increases. Please see online supplementary material for a spinning 3D plot. This relationship is demonstrated in brain maps depicting correlations between PA and brain activity (controlling for runs used) among subjects whose SES was below the median (b) and above the median (c). Correlations between PA and activity at the left fusiform ROI are circled in white ($p < .005$ uncorrected). Only the lower SES map shows a significant area of positive correlation. Note that because statistical interactions can be quite skewed by the presence of individual points that exert an undue influence on the interactive relationship, five points that exerted undue influence on the interaction have been excluded from the scatterplot (see text).

Table 6 *Voxelwise analysis of SES × PA interactions*

Region		Coordinates						Peak Z	<i>p</i> (uncorr.)	Cluster partial <i>R</i> ² : interaction term	Cluster size (voxels)
MNI	Talairach	MNI (x,y,z)			Talairach (x,y,z)						
L FG	L FG	-34	-58	-16	-34	-57	-11	4.24	0.000	0.31	215
R Cb	R Cb	14	-54	-20	14	-53	-14	3.56	0.000	0.15	61
L MOG	L MOG	-40	-72	2	-40	-70	5	2.92	0.002	0.28	28
L HG	L PCG	-54	-10	10	-53	-9	10	2.77	0.003	0.17	24
R STG	R STG	62	-26	6	61	-25	7	3.01	0.001	0.15	7
R SFG	R MeFG	16	60	4	16	58	1	2.84	0.002	0.11	30
R STG	R STG	62	-12	-2	61	-12	-1	2.67	0.004	0.18	24
L SFG	L MeFG	-14	64	8	-14	62	4	2.65	0.004	0.12	13

Note: Interactions represent regions in which the relationship between PA and activity varied as a function of SES. The first four peaks (L FG, R Cb, L MOG, L HG) represent regions in which lower SES children tend to exhibit a positive association between PA and activity, but where higher SES children tend to show no relationship or a negative association. The last four peaks (2 in R STG, and 1 each in R SFG and L SFG) represent regions in which higher SES children tend to show a positive association between PA and activity, but lower SES children do not. All listed regions retained significance when excluding points exerting undue influence on the interaction term (as measured by the difference in the standardized beta coefficient when deleting the case) (Pedhazur, 1997). FG = Fusiform Gyrus; ITG = Inferior Temporal Gyrus; Cb = Cerebellum; STG = Superior Temporal Gyrus; MOG = Middle Occipital Gyrus; SFG = Superior Frontal Gyrus; MeFG = Medial Frontal Gyrus; HG = Heschl's Gyrus; PCG = Precentral Gyrus.

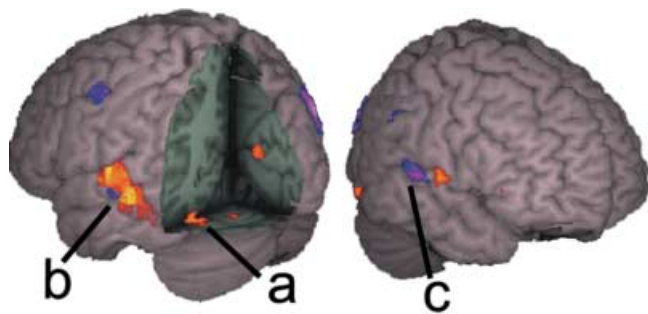


Figure 2 *Correlations of PA and activity in left fusiform and superior temporal gyrus regions, across a median split of SES. As in Figure 1, although all analyses were conducted using SES as a continuous variable, the continuum of SES has been schematically represented by dividing subjects by SES median split. Red-yellow represents correlations between PA and brain activity among children below the median SES, while blue-purple represents correlations between PA and activity among children above the median SES. Lower SES children show a positive correlation between PA and activity in (a) left fusiform (interaction cluster peak -34, -58, -16). This correlation is not observed in higher SES children. While both lower SES and higher SES children show areas of positive correlation between PA and activity in (b) left perisylvian cortex (interaction cluster peak -54, -10, 10) and (c) right perisylvian cortex (interaction cluster peak 62, -26, 6), the size of the regions exhibiting these correlations are qualitatively much larger in lower and higher SES children, respectively. Maps are depicted at $p < .005$ uncorrected.*

Discussion

The relationship between phonological awareness, SES, and brain activity was investigated in a group of

socioeconomically diverse young readers who exhibited a broad range of phonological skill levels, including a spectrum of below-average abilities that were designed to be relatively equivalent across SES. Results showed that SES – a proxy measure for a child's environment and experiences – can systematically modulate previously documented brain-behavior relationships in reading. Specifically, as SES levels decreased, brain-behavior relationships were stronger, whereas as SES levels increased, brain-behavior relationships were attenuated.

The literature-based ROI in the left fusiform gyrus was located in the region of occipito-temporal cortex that is particularly responsive to visually presented words relative to other types of visual or verbal stimulation (Brunswick *et al.*, 1999; Cohen, Lehericy, Chochon, Lemer, Rivaud & Dehaene, 2002; Fiez *et al.*, 1999; McCandliss *et al.*, 2003; Paulesu *et al.*, 2001; Polk & Farah, 2002; Price *et al.*, 1996). In general, as children improve in reading skill, they are more likely to show reading-related activity in this region (B.A. Shaywitz *et al.*, 2002). Similarly, the literature-based ROI in the left superior temporal gyrus was located in a region of perisylvian cortex that is active in typically developing children during reading and phonology tasks (Temple *et al.*, 2001; Turkeltaub *et al.*, 2003). Across childhood and early adulthood, increased phonological skill is associated with increased perisylvian activity to reading tasks (Turkeltaub *et al.*, 2003). Brain-behavior relationships have thus been reported for both of these regions, with higher reading and phonological skills typically associated with increased activity to reading tasks. However, the evidence presented here suggests that a child's background and experiences, as operationalized by SES, can systematically influence the relationship between standardized measures of reading precursor skills and reading-related brain activity.

Children who demonstrate a range of phonological skill levels in the context of a lower SES environment show evidence for strong brain-behavior relationships. In these children, phonological skill level is positively predictive of activation in the left fusiform region that supports rapid visual word recognition. This indicates that, in these children, the cognitive precursors to reading are influential in predicting reading-related activity, as has been reported previously in the literature (B.A. Shaywitz *et al.*, 2002). In contrast, as the SES of the population increases, children demonstrating a similar range of phonological skill show an attenuated brain-behavior relationship in this region. This suggests that, among children who are likely to have adequate access to literacy resources, the relationship between reading precursor skills and left fusiform activity to reading may, to an extent, be reduced, marking an atypical relationship between cognitive skill and brain activity. A marginally significant PA \times SES interaction was also observed in the left superior temporal region, demonstrating a similar trend.

Although further research is required to shed light on the mechanisms underlying this phenomenon, we offer speculation about several possibilities. Previously, we demonstrated a behavioral PA \times SES interaction for pseudoword reading. That is, with higher phonological skill, children were generally reading well regardless of socioeconomic background. However, among children scoring at lower PA levels, higher SES was consistently associated with better performance in pseudoword reading (Noble *et al.*, 2006). We conjectured that increased exposure to print associated with higher SES backgrounds may serve to buffer low phonological skill in these children. The present dataset suggests the possibility that, among higher SES children with the very lowest phonological skill, such a buffering effect may have taken place, such that fusiform activation is actually higher than that seen at similar PA levels among lower SES children (see Figure 1). Perhaps exposure to reading-related activities has led to increased recruitment of the left fusiform gyrus during reading, despite poor phonological skill.

These neuroimaging results thus provide insight into the possible mechanisms underlying the previously reported behavioral interaction. The present study suggests that the locus of the neural correlates of the observed interaction between PA and SES in reading skill lies primarily in the left fusiform gyrus. This region has been consistently associated with visual-orthographic processes in reading (Brunswick *et al.*, 1999; Fiez *et al.*, 1999; McCandliss *et al.*, 2003; Price & Devlin, 2004; Price *et al.*, 1996), and has been systematically and positively associated with reading skill level in children, including children with reading difficulties (B.A. Shaywitz

et al., 2002). The current findings indicate that responsiveness of this visual-orthographic region is influenced by both individual differences in phonological skill and by environmental differences in literacy resources. Importantly, these two factors interact in a particularly informative way. Under circumstances of low resources for literacy support, the degree to which children learn to recruit this region during a reading task may be tightly linked to differences in phonological ability. Circumstances of higher resources for literacy support, however, reduce the influence of individual differences in phonological abilities. Such findings may provide insight into the means by which increased literacy resources associated with higher SES may impact the development of orthographic processes. It is possible that children in such environments with low phonological abilities receive additional instruction in orthographic processes such as letter recognition, decoding print, and increased overall print exposure. Such a hypothesis could lead to novel research to examine such possibilities, and may lead to insights in effectively targeting the specific needs of children in lower SES environments.

Several neural regions demonstrated trends showing the converse interaction of that described above, in which higher SES children tended to show a positive association between PA and activity, whereas lower SES children did not (see Table 6, Figure 2). Specifically, such interactions were observed in right superior temporal gyrus and bilateral superior frontal gyri. Interestingly, Shaywitz and colleagues recently contrasted the functional neural profile of three groups of adult readers: two groups who had tested in the reading-impaired range as children, and one group of never-impaired readers (S.E. Shaywitz, Shahywitz, Fulbright, Skudlarski, Mencl, Constable, Pugh, Holahan, Marchione, Fletcher, Lyon & Gore, 2003). Of the previously impaired groups, one group subsequently demonstrated accuracy-improved reading as adults, whereas the other group showed persistently poor reading. During a pseudoword reading task, the accuracy-improved readers activated right perisylvian and superior frontal cortices – the very regions that are shown here to be positively associated with PA among higher SES children. The authors attributed this activation to compensatory reading systems. Importantly, another key difference was present across the groups as well: the persistently poor readers were significantly more likely to come from a disadvantaged school relative to the never-impaired adults, whereas the accuracy-improved readers were not. Thus, children who were selected for poor reading in the context of a higher SES environment were more likely both to show improved reading as adults, and to engage right perisylvian and superior frontal regions during a reading task. When

considered together with those results, the present study suggests that, as phonological skill improves, a higher SES environment may lead a child to engage such areas – perhaps via more extensive early literacy exposure – in order to compensate for atypical activation of the brain systems that typically underlie reading. The mechanisms underlying the association between PA and the recruitment of these areas, as well as the computational processes performed in these regions, remain to be investigated.

SES differences have long been associated with differences in reading outcome (Adams, 1990; Bowey, 1995; Dickinson & Snow, 1987; Hecht *et al.*, 2000; Lonigan *et al.*, 1998; Raz & Bryant, 1990; White, 1982; Whitehurst, 1997). One possibility is that some children with lower phonological skills, who might have otherwise been poor readers, benefited from increased exposure to print, phonological manipulation, and the principles of mapping letters to their sounds which, in essence, served to ‘buffer’ their skills, leading to higher achievement in reading. Children are much more likely to experience such resources as family SES increases (Adams, 1990; R.H. Bradley, Corwyn, Pipes McAdoo *et al.*, 2001; Hecht *et al.*, 2000; Raz & Bryant, 1990; Whitehurst, 1997), potentially contributing to the SES gap in achievement (R.H. Bradley & Corwyn, 2002; R.H. Bradley, Corwyn, Burchinal *et al.*, 2001; Brooks-Gunn & Duncan, 1997; McLoyd, 1998). We may theorize that this access to literacy resources in turn stimulates the use and development of reading-related brain regions. If this hypothesis is accurate, it would further suggest that many low-achieving readers would demonstrate neurobiologically typical brain responses to print (e.g. S.E. Shaywitz *et al.*, 2003), and that improved access to resources would lead to greater achievement.

Finally, several caveats in interpreting the preceding results should be issued. Although the preceding discussion has focused on the statistical effect of SES on a previously documented brain–behavior relationship, it should be noted that interactions are reciprocal. The direction of causality should thus not be assumed, and it should be recognized that the present results could equivalently be explained as differences in reading-related brain activity that influence the relationship between SES and reading ability. In addition, our measure of SES was based entirely on parental self-report, which may have been biased. Ideally, by incorporating relatively objective measures that involve direct home and school observation (R.H. Bradley, Corwyn, Pipes McAdoo *et al.*, 2001; Morrison, Griffith & Alberts, 1997), future research may better quantify SES, and shed further light on the means by which SES differences modulate the relationship between PA and reading achievement. Though we suspect that differential exposure to literacy resources may be a primary pathway, this hypothesis needs to be formally

tested, as do other potential mechanisms involving nutritional, socioemotional, health, or other school factors.

In sum, the work presented here has both methodological and theoretical implications for studying the neurobiological basis of reading. From a methodological perspective, SES – or experiential factors for which it can be considered a reasonable proxy – can systematically influence brain–behavior relationships. In regions that support the typical development of reading, social and cognitive factors demonstrate a multiplicative influence on brain activity, such that the effect of one cannot be properly measured without taking the other into account. The relationship between PA and the neural response to reading is thus fundamentally intertwined with SES, rendering any study that examines the neural basis of reading development without accounting for SES somewhat limited in its interpretability.

This work also helps to frame theoretical issues regarding the factors that influence individual differences in the emergence of reading skills. Social, cognitive, and neurobiological systems are interrelated, with each contributing to achievement outcomes. By bridging research across these different levels of explanation, we will broaden our insight into the typical and atypical manifestations of reading development. Further, by considering the neurobiological mechanisms that underlie the relationship between cognition and achievement, we open new avenues to investigating and understanding the socioeconomic gap in reading achievement.

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Supplementary Material

The following supplementary material is available for this article:

Video Clip S1. *This 3D scatter plot depicts the partial correlation of PA and left fusiform activity across SES, controlling for age, task accuracy, and runs used. A significant PA × SES interaction was found (p < .006), such that PA is more strongly associated with left fusiform activation at lower SES levels, whereas this association is attenuated as SES increases. See also text Figures 1b and 1c.*

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