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Print-speech convergence predicts future reading outcomes in early readers

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Abstract

Becoming a skilled reader requires building a functional neurocircuitry for printed language processing that converges on spoken language processing networks. In this longitudinal study, functional magnetic resonance imaging (fMRI) was used to examine whether convergence for printed and spoken language in beginning readers predicts reading outcomes two years later. Print-

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Author Contributions: J. Preston facilitated behavioral data management, conducted data analysis, and drafted the manuscript. Data analytic plan and fMRI data analysis was conducted by P. Molfese. W.E. Mencl and S.J. Frost contributed to the study design and oversaw fMRI data management. R. K. Fulbright assisted with MRI data acquisition parameters and conducted quality checks of MRI data. F. Hoeft and N. Landi assisted with data interpretation and theoretical insights and manuscript revision. D. Shankweiler provided the initial theoretical model and provided a framework on print-speech convergence in adult readers that was tested here with early readers. K. R. Pugh developed the study concept and theoretical rationale. All authors contributed to manuscript development and approved the final version of the manuscript for submission.

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speech co-activation across the left hemisphere reading network predicted later reading achievement beyond the effects of brain activity for either modality alone; moreover, co-activation effects accounted for variance in later reading after controlling for initial reading performance. Within the reading network, effects of co-activation were significant in bilateral inferior frontal gyrus (IFG) and left inferior parietal cortex and fusiform. The contribution of left and right IFG differed, with more co-activation in left IFG predicting better achievement but more co-activation in right IFG predicting poorer achievement. Findings point to the centrality of print-speech convergence in building an efficient reading circuitry in children.

The human ability to process spoken language provides a biological foundation through which printed language may be learned (Liberman, 1992). Oral language skills that require explicit phonological processing (the ability to detect, categorize, retrieve, and manipulate speech segments) are causally linked to the ability to rapidly and accurately map letters to speech sounds for successful reading (Bradley & Bryant, 1983; Wagner & Torgesen, 1987). For example, skilled readers show superior performance over poorer readers on tasks that require access to phonological information and meta-phonological skills (National Reading Panel, 2000; Shankweiler et al., 1995). Skilled readers may have detailed internal representations for speech which allows them to learn to quickly and accurately map printed language onto existing phonological representations (Elbro, 1996; Wagner & Torgesen, 1987). Additionally, skilled readers are more successful than poorer readers at learning to pair novel visual and verbal information (Hulme, Goetz, Gooch, Adams & Snowling, 2007; Vellutino, Scanlon & Spearing, 1995).

Learning to connect printed letters or words to their spoken forms is an example of a task requiring integration across modalities. Warmington and Hulme (2012) reported that children's performance on paired verbal-visual learning tasks was a strong indicator of their ability to read both real words and nonwords. The presumption is that poor integration across modalities may contribute to poor reading outcomes. At the level of brain, this implies a neurolinguistic system that is suitably adept at processing information through both spoken and printed modalities, and one that might depend upon *functional convergence* across modalities to achieve proficient reading (Braze et al., 2011; Kovelman et al., 2015; Liberman, 1992; Shankweiler et al., 2008). How this cooperative relationship between visual and auditory language processing develops within early readers' neurobiological networks and how re-organization of language systems for reading supports the development of fluent and automated reading over time are key questions with implications for both theory and practice (Dehaene, Cohen, Morais, & Kolinsky, 2015; Shankweiler et al., 2008).

Surprisingly, the contribution of cross-modal neural convergence to reading ability has only recently been explored. Studies from our lab have reported a robust relationship between individual differences in print-speech co-activation in left hemisphere (LH) language regions and reading-related skills in children (Frost et al., 2009) and adults (Constable et al., 2004; Shankweiler et al., 2008). Frost et al. (2009) found that young readers' behavioral performance on phonological awareness tasks is associated with variability in print-speech convergence in LH language related regions - the better the child's phonological awareness, the smaller the difference between activation levels for print and speech in LH networks,

especially the superior temporal gyrus (STG). A study with young adults showed a similar brain-behavior pattern for reading comprehension skill (Shankweiler et al., 2008). In LH inferior frontal gyrus (IFG) greater convergence of activation for auditory and printed sentences was associated with higher reading comprehension scores. Compatibly, Blau et al. (2010) reported that 9 year olds' responses to letters and speech sounds in planum temporale and Heschl's gyrus correlated with word and pseudoword reading. McNorgan et al. (2013) observed that typically developing readers ages 8-13 showed significant correlations between phonological awareness (elision) and their functional activation in a cross-modal (auditory-visual) rhyme judgment task in fusiform gyrus, posterior superior temporal sulcus, and planum temporale. Poor readers did not show this cross-modal integration, suggesting that they may fail to engage the same system when processing phonological information in different modalities. In these studies, individual differences in reading skills correlated with the degree to which print and speech materials engage overlapping neural networks.

The neural circuitry for reading has been extensively studied in children and adults and there is strong consensus on the topology (see Pugh et al., 2010 for a review). Skilled readers show robust activation and functional connectivity across LH dorsal (temporoparietal, TP), ventral (occipitotemporal, OT) and inferior frontal networks along with subcortical networks in print processing tasks (Pugh et al., 2010; Pugh et al., 2013; Shaywitz et al., 2002). These functional difference for print are evident early on; we recently reported that heightened activation in reading-related LH cortical regions (IFG, TP and OT) and subcortical networks were associated with better concurrent decoding skills in children learning to read (Pugh et al., 2013). For both children and adults with poor reading achievement, there are marked functional differences in activity generated in these systems during reading. Specifically, poor readers tend to under-activate LH networks used by strong readers (Brunswick, McCrory, Price, Frith & Frith, 1999). Additionally, poor readers often show evidence of two, apparently compensatory, patterns associated with their LH dysfunction: an increased functional role for right hemisphere (RH) posterior sites (Shaywitz et al., 1998) and increased bi-hemispheric IFG activation (Brunswick et al., 1999; Shaywitz et al., 1998; 2002). In the current study we target bilateral IFG, TP, and OT regions; we extend beyond cross-sectional correlations toward developing a neurobiological account of how individual differences in print-speech convergence at the initial stages of learning to read actually predict later reading outcomes.

A few longitudinal studies of neural activation patterns support the expectation that functional activation for print in critical regions can predict future reading performance. For example, in children as young as 8 years, improvement in decoding has been found to positively correlate with functional activation in LH IFG and LH basal ganglia (McNorgan, Alvarez, Bhullar, Gayda, & Booth, 2011) as well as RH OT and bilateral middle temporal gyrus (Hoeft et al., 2007). No studies, to date, have examined print-speech convergence as an indicator of later reading. In the current investigation, we explore for the first time the hypothesis that print-speech convergence in LH and RH networks (previously implicated in skilled and less skilled reading) predict reading two years later as children transition from learning to read to fluent and automatic decoding. We ask whether convergence differences account for outcomes above and beyond behavioral measures or general activation for print and speech.

Method

Participants

Recruiting focused on obtaining a range of reading ability, from skilled readers to poor readers. Children entered into the study during a three-year recruiting wave and were followed for two years. Data collection ended when the two-year follow-up visits were completed on all participants who remained available for the study. Sample size was based on power analyses informed by brain-behavior correlational studies of reading in young adults (Shankweiler et al., 2008) and prior longitudinal studies that had identified significant functional brain predictors in multiple regression models (Hoeft et al., 2007). From the full sample of 128 children who provided longitudinal behavioral data, the current study includes all 68 children who met the following criteria, regardless of their reading ability: (a) completed functional magnetic resonance imaging (fMRI) and whose fMRI data met our quality standards (outlined below), and (b) also met the following demographic criteria: age 6-10 years at entry into the study (Time 1, T1), native English speakers, no history of hearing or vision impairment, intellectual disability, or developmental disability. In addition, participants reported here include children who also provided behavioral data on our outcome reading measure at the two-year follow-up (Time 2, T2). A summary of demographic data and performance on behavioral tasks is reported in Table 1.

Behavioral Measures

To evaluate reading skills, the Woodcock Johnson Test of Achievement-III (WJ, Woodcock, McGrew, & Mather, 2001) was administered at both T1 and T2. The primary outcome variable of the study was the WJ Broad Reading Composite score (WJBR), which consists of Letter Word Identification (recognizing letters and reading real words of increasing difficulty), Reading Fluency (speeded reading of sentences), and Passage Comprehension (reading and understanding short passages). Additional reading measures included accuracy of single words and pseudowords assessed by the Basic Reading subtest of the WJ (Letter-Word Identification and Word Attack), and the Phonemic Decoding and Sight Word Efficiency subtests of the Test of Word Reading Efficiency (TOWRE, Torgesen, Wagner, & Rashotte, 1999).

IQ was assessed for descriptive purposes by the Wechsler Abbreviated Scales of Intelligence (WASI, Wechsler, 1999) and spoken language skills were evaluated using the Peabody Picture Vocabulary Test-III (PPVT, Dunn & Dunn, 1997) and the oral language subtests of the WJ-III Tests of Achievement (Woodcock et al., 2001). In addition, the Comprehensive Test of Phonological Processing (CTOPP, Wagner, Torgesen, & Rashotte, 1999) was administered to evaluate phonological awareness (Elision and Blending Words).

Functional MRI Task

To assess functional activation in relation to print and to speech, children participated in a picture identification task (see Frost et al., 2009). An event-related design was used in which a picture initially appeared on the screen followed by a series of comparison items. Comparison items were either printed or spoken real words or pseudowords presented in separate trials with a jittered inter-stimulus interval of 4-7 sec. There were four sets of

pictures and comparison items per functional run. Words/pseudowords either matched the picture (20% of trials) or did not match the picture on the screen (80% of trials). Participants responded by button press to indicate a match or mismatch. To average over similar response types, we restrict our analysis to functional activation for processing of printed and spoken tokens for the mismatch trials (collapsing words and pseudowords). Within-scanner performance is reported in Table 1.

fMRI Acquisition and Processing

Functional MRI data were acquired on a Siemens 1.5T (Sonata) scanner on a separate day from the behavioral testing at T1. Participants' heads were enclosed in a standard head coil with padding to stabilize the head against movement throughout the scan. Functional images were collected as 20 axial-oblique slices using a single-shot, gradient echo, echo planar (EPI) acquisition (flip angle 80°; echo time [TE] 50ms; repetition time [TR] 2000ms; field of view [FOV] 200mm × 200mm; slice thickness was set to 6mm without gap). All children received a minimum of 6 and a maximum of 10 functional runs. Additionally, a high resolution anatomic image was acquired using the Magnetization-Prepared Rapid Gradient-Echo (MPRAGE) pulse sequence (flip angle 8°; TE 3.65; TR 2000ms; FOV 256 × 256mm; voxel resolution 1 × 1 × 1mm).

Analysis of functional data was performed in AFNI (Cox, 1996), after first adjusting for differences in slice acquisition times and motion, co-registered to the individual's high-resolution anatomical data, and linearly normalized to a standard template (Colin27) using a single concatenated transform. Data were smoothed with an 8mm full width of half maximum (FWHM) kernel and submitted to a standard general linear model with Gamma-based hemodynamic response function, baseline drift terms, and 6 motion parameters (3 translation, 3 rotation).

Identifying Co-activation in Regions of Interest

The Reading Network included regions of interest (ROIs) selected based on a model of the canonical reading circuit developed from our previous work (Pugh et al., 2010; Pugh et al., 2013). Four primary ROIs in each hemisphere were anatomically identified using atlas-defined regions (Eickhoff-Zilles SPM Anatomy Toolbox v1.8). These regions included bilateral IFG (pars opercularis and pars triangularis), TP regions including STG (anterior and posterior) and inferior parietal cortex (IPC, inferior parietal lobule and supramarginal gyrus), and the fusiform gyrus that contains the OT region. Within each anatomical region, we created a metric of speech-print convergence based on *co-activation*, defined as the total number of voxels for each subject that were significantly activated ($p < .01$) for both speech and print stimuli (conjoint probability $p < .0001$). This threshold used in our previous investigation (Frost et al., 2009) was chosen since it revealed reliable individual differences in co-activation that were predictive of relevant behavioral differences. Co-activation in the Reading Network was the sum of the co-active voxels in these four regions within the respective hemispheres. In addition, the number of voxels activated at $p < .01$ across the whole brain (WB) for speech and print stimuli was computed to control for relative degree of brain activation for each participant. It is important to point out that, although we presume that co-activation as measured here reflects neuronal populations that are responding to both

modalities, we are limited by the spatial resolution of fMRI technology and results can only be interpreted within this resolution.

Data Analysis

The outcome variable was WJBR at T2. The primary analysis involved predicting T2 WJBR scores from T1 co-activation summed across the Reading Network in both the left and right hemispheres, while controlling for age at T1 and WB activation for both print and speech stimuli. We also conducted analyses of the individual ROIs of the Reading Network to gain insight into the relative contribution of each region. Although the main focus was on establishing whether convergence within the reading circuit predicts future reading performance, our previous work has indicated that convergence is correlated with concurrent (T1) reading skill, and we therefore conducted an analysis to rule out the possibility that any observed predictive relationship between convergence and T2 reading could be attributed solely to a third-order correlation with T1 reading performance (i.e., autoregressive effects).

Results

Figure 1 shows a map of regions associated with significant ($p < .01$) activation to printed stimuli, spoken stimuli, and both printed and spoken stimuli across the entire cohort. Inspection of the figure reveals that readers strongly engaged the canonical Reading Network for printed stimuli and much of this network was also engaged for speech stimuli.

The raw correlation between T2 WJBR and co-activation was significant for LH Reading Network ($r = .374, p = .002$) but not for RH Reading Network ($r = .197, p = .107$). As described above, the primary analysis connecting brain activation with later reading scores included a multiple regression predicting T2 WJBR from T1 co-activation within the pre-defined Reading Network, while controlling for T1 age and whole brain (WB) activation for print and for speech. Results from this regression are presented in Table 2 and suggest that the model accounted for significant variance in T2 reading. Specifically, T1 co-activation in the LH Reading Network was the only significant predictor of T2 reading scores. Figure 2 displays a scatterplot of this relationship, plotting T2 WJBR reading scores against T1 co-activation for LH Reading Network (with T1 age, WB print activation, and WB speech activation, and RH Reading Network co-activation partialled out).

Next, we explored how co-activation within specific regions accounted for variance in T2 reading. Each of the eight regions that comprised the Reading Network (left and right IFG, IPC, STG, and fusiform) were made available in a stepwise regression model ($p < .05$ to enter, $p > .10$ to remove). Results are shown in Table 3. The control variables were again force entered first but were not significant. However, the stepwise regression model resulted in entry of four ROIs: LH IPC (Step 2), LH IFG (Step 3), LH fusiform (Step 4), and finally RH IFG (Step 5). This suggests independent contribution of co-activation in each of these regions in predicting later reading. Note that co-activation in LH IFG, IPC and fusiform were positively associated with reading outcomes, but RH IFG was negatively associated with later reading achievement.

Finally, given our previous findings (Frost et al., 2009; Shankweiler et al., 2008), we questioned whether print-speech convergence effects might be attributable to correlations with T1 reading scores ($r=.267, p=.033$). In order to assess whether our findings might be due to a third order correlation with T1 reading we ran an additional regression (see Table 4) in which we entered co-activation in the LH Reading Network and T1 reading scores as predictors of T2 reading performance. Four participants were missing T1 reading scores and thus the analysis was conducted on 64 children. The results demonstrate that the effects of LH co-activation cannot be accounted for by a spurious third order relation to T1 reading scores. Also note that a stepwise regression assessing the variance added beyond T1 reading autoregressive effects showed that co-activation in the LH Reading Network independently contributed variance in addition to the of the variance in reading outcome accounted for by T1 reading (n.b., If the control variables and co-activation in the RH Reading Network are also made available in stepwise regression or entered in backward regression, only the LH co-activation and T1 reading scores significantly contribute to T2 reading).

Discussion

This study examined the neurobiological underpinnings of reading achievement in young readers as a function of print-speech convergence in key networks two years earlier. Results reinforce the notion, which has been emphasized in behavioral research, that learning to read is better understood as an achievement involving synthesis of speech and print than as simply a visual-orthographic learning challenge (cf. Warmington & Hulme, 2012; Hulme et al., 2007). This longitudinal study extends our previous findings of concurrent relationships in children and adults (Frost et al., 2009; Shankweiler et al., 2008). Empirically, cross-modal brain activity in the language network accounts for significant variance in reading achievement two years later while controlling for general activation for print or speech alone (which by chance could have produced more overlap) and for initial scores on the same reading tests (ruling out third order correlations with T1 reading ability). Thus, children whose early language experiences reinforce connections between speech and print are developing an overlapping organization of language cortex that supports reading (Dehaene et al., 2015). This is the predicted consequence of a biological system built for language used to support both speech and reading (Joanisse & McClelland, 2015). Whereas previous studies have shown that functional response to print in children is associated with concurrent reading (Pugh et al., 2013) and reading development (Hoeft et al., 2007; McNorgan et al., 2011; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003), the present study shows unequivocally that print-speech convergence is the operative construct in developing a fluent reading system.

The loci of these convergence effects is unsurprising as IFG and IPC have been previously shown to be general overlap regions in adults while processing language (Constable et al., 2004). Furthermore, the inverse relationship of LH and RH IFG in predicting future reading achievement is in agreement with models indicating that RH compensation is a feature of disrupted LH circuits in individuals with reading disability (Pugh et al., 2010), and data showing rightward shifts for print processing in poor readers (Pugh et al., 2008). The critical element added here is that children with poorer reading trajectories over a two year period not only utilize LH IFG less and RH IFG more for print, but they show this pattern for both

print and speech (thus convergence). This implies a shift in core language functions in these children. LH IFG has been known to be active for phonological/articulatory coding of both spoken and printed language (Price, 2012; Pugh et al., 2010), which is foundational for early reading. The increased RH engagement for processing phonological information observed in adolescent poor readers (Pugh et al., 2008) may be evident in younger children whose trajectories for reading development are poorer. Finally, whether this rightward integration reflects compensation or failure to make age appropriate shifts to LH (Shaywitz et al., 2004; Turkeltaub et al., 2003) these data reinforce the increased RH profile of poorer readers (Shaywitz et al., 1998).

The significant effects of convergence on later reading arose across the reading network. Bilateral IFG and LH IPC are believed to be tuned to phonological coding for speech and print (Binder et al., 1997; Constable et al., 2004; Pugh et al., 2008; Shankweiler et al., 2008; Shaywitz et al., 2002) and the findings here may be biological indicators of the ability to integrate orthographic and phonological representations. At later stages, fusiform gyrus also plays a role in skilled reading (Pugh et al., 2010; Shaywitz et al., 2004), and convergence in this region also contributed to later reading. Co-activation in phonologically- and visually-tuned regions were important predictors of later reading outcomes on tasks that tap reading speed and comprehension (i.e., WJBR), suggesting that early attunement of these regions enables the circuit to build a mechanism that can support reading efficiency. Effectively utilizing these systems during reading may aid with efficient transfer of letters into sound-based representations (Wagner & Torgesen, 1987).

With respect to current understanding of the topology of print and speech organization, research on spoken word processing implicates a bilateral circuitry with key functional divisions between dorsal/frontal and ventral networks for different aspects of spoken word processing (Price, 2012). Reading networks for skilled adult readers (Price, 2012; Schlaggar & McCandliss, 2007) show substantial overlap with these spoken language networks especially in LH temporoparietal and inferior frontal networks (Constable et al., 2004; Shankweiler et al., 2008). Interestingly, studies that have contrasted literate vs. illiterate adults on spoken language tasks have shown that literacy modulates organization for speech with increased involvement of temporoparietal and inferior frontal regions in simple speech tasks (Castro-Caldas et al., 1998; Kovelman et al., 2015; Rogalsky et al., 2015). Moreover, these changes in language cortex with literate language experience also have direct consequences on quality of speech processing such that literates (with greater engagement of distributed LH parietal and inferior frontal networks for speech tasks) actually perform certain speech tasks with greater proficiency than illiterates (Rogalsky et al., 2015). Thus, the impact of literacy on speech and speech on literacy is bidirectional in that not only does learning to read impact speech processing (Dehaene et al., 2015), but it very much depends on convergence of these networks (Frost et al., 2009; Shankweiler et al., 2008). These findings support our assertion that early convergence is critical in developing efficient reading skills.

The longitudinal design enables us to move closer to achieving causal models of the neural bases of early reading success and failure. The results are consistent with behavioral studies showing associations between reading ability and verbal-visual learning (cf. Hulme et al.,

2007; Vellutino et al., 1995; Warmington & Hulme, 2012). However, questions remain about how the speech and reading circuits influence one another in development, and how integrated processing might be mutually facilitative for both modalities (Monzalvo & Dehaene-Lambertz, 2013). By utilizing theoretically-motivated neurobiological indicators of future reading achievement, the present study provides a necessary foundation for studies of the brain basis of poor reading outcomes that may be explored across languages. Children whose brains begin to leverage the reading network for cross-modal processing are likely to have better reading achievement in the future. These results reinforce that reading development emerges as a connection between spoken and printed linguistic representations.

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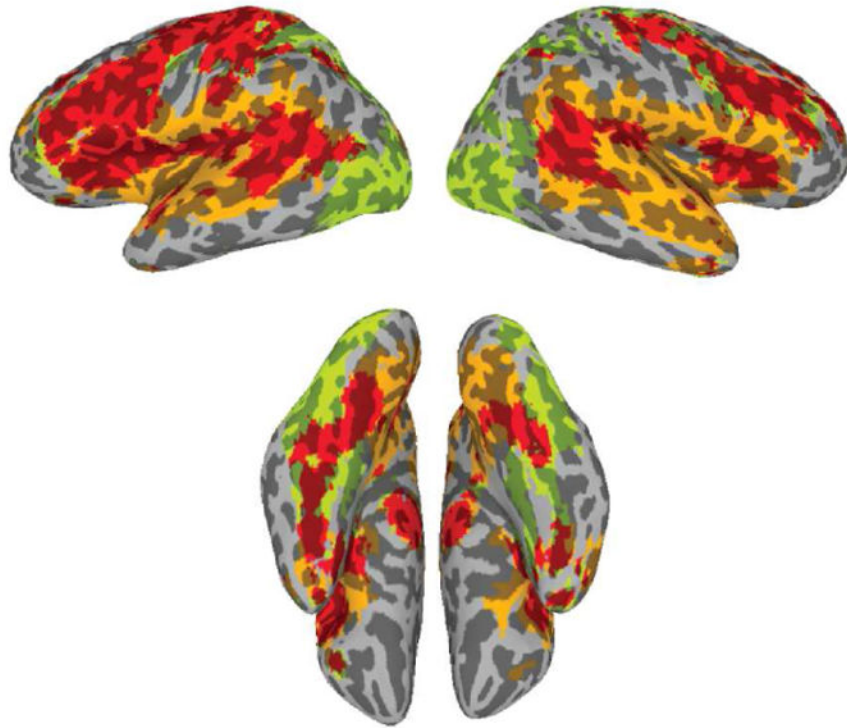


Figure 1. Regions that are activated ($p < .01$) across the sample for printed stimuli only (green), auditory stimuli only (orange), or both printed and auditory (red). Left hemisphere is shown on the left, right hemisphere on the right. Top images show lateral view, bottom images show inferior view.

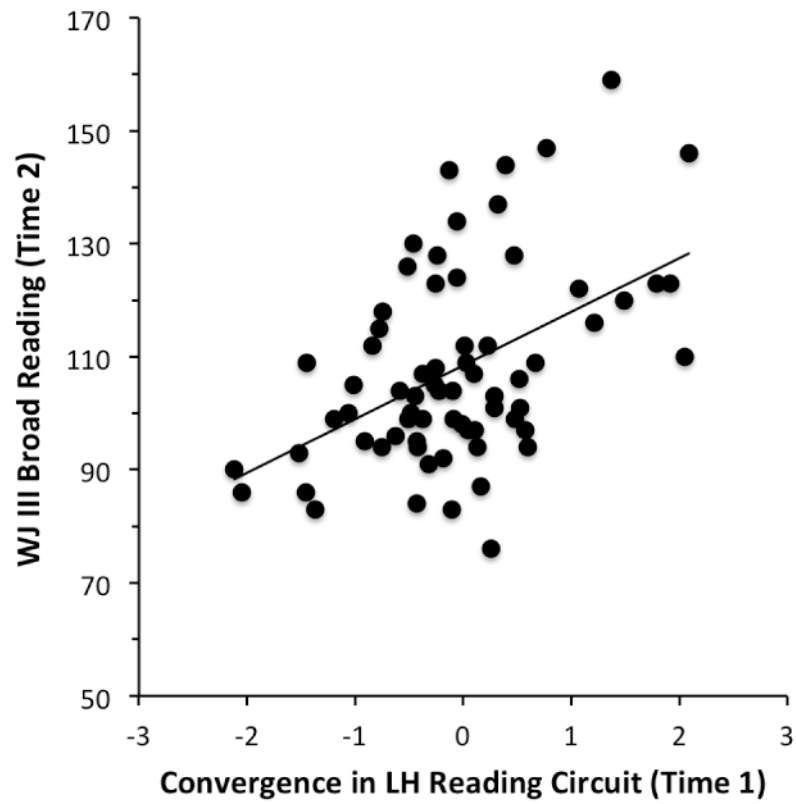


Figure 2. Time 2 reading scores plotted against standardized residuals for Time 1 convergence in left hemisphere Reading Network (co-activation for print and speech, controlling for age, whole brain activation for print and speech, and right hemisphere co-activation, $R^2 = 0.30$).

Table 1
Demographic and descriptive data for 68 children

	Time 1 mean (SD)	Time 2 mean (SD)
Age (years)	8.5 (1.2)	10.5 (1.3)
WJ-III Broad Reading	110 (19)	108 (17)*
WJ-III Basic Reading	111 (17)	106 (14)
TOWRE Sight Word Efficiency	102 (16)	102 (13)
TOWRE Phonemic Decoding	103 (17)	103 (18)
WASI Verbal IQ	111 (15)	116 (14)
WASI Performance IQ	111 (17)	111 (16)
PPVT-III	113 (13)	115 (14)
CTOPP Phonological Awareness	108 (17)	104 (15)
fMRI task percent accuracy	85 (12)	

* Note: WJ Broad Reading served as the outcome variable at Time 2

Table 2
Multiple regression predicting Time 2 Woodcock Johnson Broad Reading composite score from Time 1 print-speech co-activation in the reading network in the left and right hemispheres

<i>R</i> ²	<i>F</i>	<i>p</i>	Variable	Function	β	<i>t</i>	<i>p</i>
.30	5.4	<.001	AgeT1	Control	-.16	-1.41	.163
			WB Print activation	Control	-.60	-1.65	.103
			WB Speech activation	Control	-.12	-1.77	.083
			LH Reading Network Co-A	ROI	1.59	4.32	<.001
			RH Reading Network Co-A	ROI	-.28	-1.00	.323

Table 2 note: Co-A=Co-activation (number of voxels significantly active in the region for both print and speech stimuli), LH=Left Hemisphere, RH=Right Hemisphere, WB= Whole Brain

Table 3

Stepwise multiple regression predicting Time 2 Woodcock Johnson Broad Reading (WJBR) composite score from Time 1 print-speech activation in selected anatomically-defined regions of interest.

Model Statistics		Step 1 (force entry)			Step 2			Step 3			Step 4			Step 5				
R ²	F	p	β	t	p	β	t	p	β	t	p	β	t	p	β	t	p	
.09	1.98	.126																
			Age Time 1	-1.13	-1.09	.280	-.14	-1.18	.243	-.18	-1.55	.125	-.09	-.81	.423	-.08	-.68	.500
			WB Print activation	.04	.201	.841	-.20	-.90	.369	-.44	-1.82	.073	-.82	-2.86	.006	-.73	-2.52	.014
			WB Speech activation	.25	1.14	.257	-.13	-.55	.582	-.37	-1.46	.150	-.62	-2.30	.025	-.32	-1.05	.296
.20	4.00	.006	LH IPC				.69	3.05	.003	.53	2.31	.024	.55	2.45	.017	.47	2.16	.035
.26	4.42	.002	LH IFG							.65	2.25	.028	.64	2.29	.026	.68	2.49	.016
.32	4.78	<.001	LH Fusiform										.64	2.26	.027	.63	2.28	.026
.37	4.97	<.001	RH IFG													-.42	-2.11	.039

Table 3 note: Age at Time 1, WB print activation, and WB speech activation were force entered in Step 1. Co-activation in anatomically defined regions of interest were selected among left and right IPC, IFG, fusiform, and STG until no additional ROIs resulted in significant improvement in model fit.

WB= Whole brain, LH= Left hemisphere, RH= Right Hemisphere, IPC=Inferior Parietal Cortex, IFG=Inferior Frontal Gyrus

Multiple regression predicting Time 2 Woodcock Johnson Broad Reading (WJBR) composite score from earlier Time 1 WJBR and co-activation in the left hemisphere.

Table 4

<i>R</i> ²	<i>F</i>	<i>p</i>	Variable	Function	β	<i>t</i>	<i>p</i>
.79	112	<.001	WJBR Time 1	Control	.85	13.78	<.001
			LH Reading Network Co-A	ROI	.124	2.03	.047

Table 4 note: Co-A=Co-activation (number of voxels significantly active in the region for both print and speech stimuli), LH=Left Hemisphere