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Spoken language proficiency predicts print-speech convergence in beginning readers

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A R T I C L E I N F O

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A B S T R A C T

Learning to read transforms the brain, building on children's existing capacities for language and visuospatial processing. In particular, the development of print-speech convergence, or the spatial overlap of neural regions necessary for both auditory and visual language processing, is critical for literacy acquisition. Print-speech convergence is a universal signature of proficient reading, yet the antecedents of this convergence remain unknown. Here we examine the relationship between spoken language proficiency and the emergence of the print-speech network in beginning readers (ages 5–6). Results demonstrate that children's language proficiency, but not their early literacy skill, explains variance in their print-speech neural convergence in kindergarten. Furthermore, print-speech convergence in kindergarten predicts reading abilities one year later. These findings suggest that children's language ability is a core mechanism guiding the neural plasticity for learning to read, and extend theoretical perspectives on language and literacy acquisition across the lifespan.

1. Introduction

Learning to read transforms the brain (Dehaene et al., 2015). Specifically, recognizing words in their written form engages two key components: language proficiency, and visuospatial processing. The cross-modal integration of these auditory and visual processes results in a brain network of frontal, temporal, and parietal regions that is activated during both auditory word (speech) and visual word (print) processing, across languages and orthographies (Rueckl et al., 2015). This co-active network for auditory and visual language processes, also called *print-speech convergence*, is thought to emerge as a function of learning to read (Chyl et al., 2018). However, the cognitive abilities that precede and predict the emergence of this shared network, setting the stage for successful reading acquisition, remain unknown.

Reading acquisition presents a paradox. Despite the lengthy neurodevelopmental trajectory towards reading fluency (Turkeltaub et al., 2003), it is well established that children's spoken language skills precede and predict reading outcomes long before literacy instruction. For instance, children's vocabulary prior to age 2 significantly predicts word reading accuracy and reading comprehension five years later (Duff et al., 2015). By age 2½, children who later exhibit reading disorders demonstrate poorer spoken language ability than typical readers (Scarborough, 1990). Similarly, preschool children with family risk for dyslexia, a highly heritable, lifelong reading impairment, consistently demonstrate

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poorer phonological and syntactic skills than their peers who are not at risk for reading disability (see meta-analysis by Snowling and Melby-Lervåg, 2016). Furthermore, preschoolers' sensitivity to word sounds (e.g., rhyme and alliteration) predict reading and spelling three years later (Bradley and Bryant, 1985), while language skills at age 8 predict reading skills in adolescence (Nation and Snowling, 2004). Thus, young children's language ability is strongly associated with their reading success years later.

Similarly, the brain basis of auditory language processing is also a significant predictor of future reading ability. Speech processing in infancy differs between those with and without family risk for dyslexia (Leppänen et al., 2002; Richardson et al., 2003). Neural responses to speech sounds in infancy can further predict children's pre-reading skills prior to the start of school (Guttorm et al., 2010). These differences in auditory processing persist throughout childhood. For instance, at the start of schooling, kindergarteners at familial risk for dyslexia show reduced activation in bilateral temporal and occipitotemporal regions during a word rhyming task (Dębska et al., 2016). In a sample of Chinese kindergarteners, both phonological awareness and neurophysiological responses to speech sounds predict character reading one year later (Hong et al., 2018). This finding is particularly noteworthy because Chinese characters are less predictable in conveying phonological information than alphabetic letters. Nevertheless, despite the lower predictability of phonology in Chinese reading (McBride-Chang et al., 2005), auditory processing remains a significant predictor of future literacy outcomes. Given the critical role of language processing in reading success, children's brain development for spoken language can logically be expected to shape the emergence of the reading systems.

Reading, at its core, is the act of recognizing language in print (Frost, 2012; Perfetti, 2003). In a recent cross-linguistic fMRI study of English, Spanish, Hebrew and Chinese adult readers, Rueckl et al. (2015) observed remarkable similarity between processing spoken words and written words across languages and orthographies. To arrive at this finding, Rueckl et al. (2015) implemented two analytical approaches. First, they examined the spatial co-activation between spoken and written word processing at the whole-brain level, revealing a network of frontal, temporal, parietal and occipital regions that is consistently activated during word recognition across modalities. Second, they examined voxel-wise correlations between speech and print processing for each individual. This second analysis revealed substantial similarity in the strength of print and speech activation across the brain – in particular, a left middle temporal (MTG) region in which activation for speech and print were highly correlated across all four languages. This converging evidence across languages and methods suggested that successful literacy acquisition is contingent on the successful integration of speech and print processes, and that this *print-speech convergence* is a universal signature of proficient reading (Rueckl et al., 2015). In the present work we adopt the Rueckl et al. (2015) method to examine the development of print-speech convergence in beginning readers.

How and when do print and speech processes converge in the reading brain? To our knowledge, only a handful of studies have examined the emergence of the co-active print-speech network. Chyl et al. (2018) compared spoken and written word processing in kindergarten pre-readers to a group of age-matched peers with elementary word reading ability. While pre-readers failed to significantly activate the canonical language network when presented with visual words, age-matched beginning readers demonstrated spatial co-activation in the left inferior frontal gyrus (IFG), superior temporal gyrus (STG) and middle temporal gyrus (MTG) for spoken and written word processing (Chyl et al., 2018). These findings provide preliminary evidence that print-speech convergence emerges as a function of learning to read. Similarly, Frost et al. (2009) demonstrated that among children ages 6–10, better phonological awareness is associated with greater spatial co-activation for print and speech in the left STG. Furthermore, the extent of this print-speech convergence can predict children's word reading ability two years later (Preston et al., 2016). Together, these findings suggest that the emergence of a co-active print-speech network is associated with successful reading development. However, the antecedents of this convergence remain unknown. Given the critical role of spoken language skills and auditory processing in reading acquisition, we argue that children's spoken language ability should shape the foundations of a converging print-speech network for literacy in emerging readers.

Learning to read requires children to recognize language in its written form. Here we examine, for the first time, the association between spoken language abilities and the development of print-speech neural convergence in beginning 5-year-old readers. Of particular interest is the cross-modal integration of print and speech processes in left frontal and temporal regions associated with auditory word processing (Price, 2012), as well as print-speech co-activation in proficient readers (Frost et al., 2009; Preston et al., 2016; Rueckl et al., 2015). We additionally chose to examine fusiform co-activation in response to recent literature suggesting the cross-modal involvement of occipitotemporal regions during phonological processing in 5–6 year olds (Wang et al., 2018), as well as anatomical connectivity between left fusiform and middle temporal regions that precedes word reading (Saygin et al., 2016). We hypothesize that the extent of kindergarten children's print-speech convergence in these regions will be related to both their early reading ability and their spoken language proficiency.

In the present study, we examine print-speech convergence in beginning readers by extending Rueckl and colleagues' (2015) analytic approach for characterizing print-speech convergence to our developmental inquiry. Our sample included 133 kindergarteners who completed standardized assessments of language and literacy, 68 of whom also completed a spoken word and a written word processing task during fMRI neuroimaging. Using conjunction-and logic, we examined spatial co-activation for speech and print at the whole brain level, as well as in left frontal, temporal and fusiform regions that are engaged in language processing across modalities in proficient readers (Shankweiler et al., 2008). We then assessed voxel-wise correlations between print and speech processing, and examined an *a priori* left MTG region thought to demonstrate print-speech convergence in adults across languages (Rueckl et al., 2015). Evidence from these two approaches revealed the extent of print-speech convergence in beginning readers, as well as the mechanisms that drive convergence, and predict reading outcomes.

2. Method

Participants. 133 kindergarteners, ranging from 5.1 to 6.4 years old (mean age = 5.73 years, SD = 0.34, 56% male), were recruited through their public schools in a large, diverse community in California, and participated in a study of language and literacy development. Demographic information obtained through parent report indicated that 49% of participating children were White, 13% were Asian, 3% were Black or African American, and 26% were of multiracial heritage. Additionally, 23% identified as Hispanic or Latinx. Participants were linguistically diverse, as 20% of children grew up in homes that spoke languages other than English, most commonly Spanish and Chinese. The sample was of relatively high socioeconomic status as defined by maternal education (mean years of schooling = 17.29, SD = 2.36). All procedures were approved by the University of California San Francisco IRB, and participants were compensated for their time.

Inclusion Criteria for Neuroimaging Analysis. *Cognitive.* Participants were required to have standard scores above 85 on a test of nonverbal intelligence (Kaufman Brief Intelligence Test; Kaufman and Kaufman, 2004). All participants were proficient speakers of English, with standard vocabulary scores above 85 (Peabody Picture Vocabulary Test [PPVT]; Dunn and Dunn, 2007). Some participants had varied exposure to other languages as well, as is typical of the area. *Biological.* Participants were physically healthy and had no metal implants. Exclusion criteria included developmental delays, significant hearing loss, or any other neurological conditions. Both left- and right-handed children were included. A laterality index was calculated for the five left-handed children in the sample to ensure left lateralization of auditory language processing. One child showed greater right hemisphere activation; however, their inclusion in MRI analyses did not alter results. *Data quality.* 77 participants successfully completed both fMRI tasks. The smaller number of neuroimaging participants is due to attrition between the behavioral and the neuroimaging visits, which were scheduled approximately one month apart. Of the participants who returned for neuroimaging, fatigue also precluded some children from completing both the auditory and the visual fMRI tasks. An additional 9 children were excluded due to motion artifacts (more than 40% of TRs censored due to framewise displacement > 0.5 mm), leaving a sample of 68.

Longitudinal Participants. Of the 68 participants in the neuroimaging subsample, 49 returned for behavioral testing one year later, in the winter term of 1st grade (mean age = 7.13 years, SD = 0.32, 49% male). There were no significant differences in maternal education, language or literacy skills between children who did and did not return for longitudinal testing.

Neuroimaging Language and Literacy Measures. Participants saw or heard two words in sequence and indicated via button press whether the two words were the same or not (e.g., "picture" – "picture" = yes, "rabbit" – "pencil" = no). The auditory and visual modalities were separated into two different 3.8 min functional runs. During each 6 s trial, children were presented with Word 1, followed by Word 2 2000 ms later, followed by a 2000 ms question mark. In this block design, each run included 6 blocks separated by 12 s inter-block rest periods. Each block included 4 trials, with a total of 24 trials (12 matching) per run/modality, randomized across the blocks.

Children were trained on the neuroimaging tasks outside of the scanner. First, an experimenter introduced the auditory matching task rules. Children were read example word pairs, and asked to decide whether or not the two words in a pair "matched" (were identical). Next, the experimenter introduced the button box, and children completed 8 practice trials on a laptop using the button box to record their answers. If participants responded incorrectly to multiple pairs, they repeated the 8 practice trials; however, the vast majority of participants achieved ceiling or near-ceiling accuracy during the first practice session. This process was then repeated with the visual word matching task. All practice items were distinct from stimuli used in the experimental tasks.

The words used in the fMRI tasks were high frequency nouns, typically acquired prior to age five according to two age of acquisition indices (Gilhooly and Logie, 1980; Kuperman et al., 2012). All words had one or two syllables, and were an average of 4.23 phonemes long. Stimuli were matched for the number of syllables and phonemes within each word pair. Words were phonologically and visually distinct from one another within non-matching pairs (e.g., "cherry" – "puzzle"). Because participants were beginning readers, stimuli used in the visual word matching task were chosen from pictures of kindergarten classrooms with high frequency words on the walls (e.g., house, dog, pencil, birthday), and from publicly available 1st and 2nd grade spelling lists, to ensure their familiarity. T-tests showed no significant differences in phoneme length, age of acquisition, familiarity, written frequency or imagability between words that appeared across tasks, or in matching as compared to non-matching pairs.

Behavioral Language and Literacy Measures. All participants completed standardized behavioral assessments of language and literacy skills. In kindergarten, language ability measures included tests of receptive vocabulary (Peabody Picture Vocabulary Test [PPVT-4]; Dunn and Dunn, 2007), expressive vocabulary (Picture Vocabulary subtest, Woodcock-Johnson IV Tests of Achievement; Schrank, Mather and McGrew, 2014), oral comprehension (Schrank et al., 2014), and an experimental but commonly used task of morphological awareness (Apel et al., 2013). Phonological awareness was assessed using the Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP-2; Wagner et al., 2013). Reading ability measures included Letter-Word Identification, Passage Comprehension and Word Attack subtests of Woodcock-Johnson IV (Schrank et al., 2014). Importantly, the Passage Comprehension task for beginning readers is heavily supplemented by pictures. The task begins by testing children's understanding of the symbolic nature of print, and asks participants to match a symbol with a picture or phrase. More advanced items require children to read a sentence and fill in a missing word. Children who returned for longitudinal data collection in 1st grade completed the same language and literacy measures, with the exception of Word Attack.

Procedure. Kindergarteners completed two visits to the lab, first for the behavioral and second for the neuroimaging assessments. During their first session, scheduled between October and January of their first year of formal schooling, children completed behavioral assessments. During the second visit, approximately one month later (mean = 33 days, range: 1–141), children participated in fMRI neuroimaging. On average, children were scanned after 3.2 months of schooling (SD = 1.6 months). The number of days between behavioral testing and neuroimaging was not related to any behavioral measures or task activation.

During fMRI neuroimaging, snugly fitting padding was used to dampen background scanner noise and minimize head movement, while headphones delivered experimenter instructions and auditory stimuli directly to the participants' ears. The tasks were delivered via E-Prime software (Psychology Software Tools, Pittsburgh, PA). Participants viewed stimuli on a screen with a mirror mounted on the head coil and responded using a button box. 49 children returned one year later, in the spring of their 1st grade year, for follow-up behavioral assessments.

fMRI Acquisition Parameters. Due to equipment upgrades, neuroimaging data was collected at two sites with different versions of a 3T Siemens scanner. The scanning procedure was identical across sites, but image acquisition parameters differed, and are presented separately below. Scanner differences were examined, and we found no significant differences in task vs. rest activation. Nonetheless, scanner was included as a binary regressor in general linear models.

Data at Site 1 were acquired with a 3T Siemens TRIO whole-body MRI scanner using a 32-channel whole-head coil. Whole-brain functional images were acquired using a gradient-echo echo-planar pulse sequence [repetition time (TR) = 2000 ms, echo time (TE) = 28 ms, flip angle (FA) = 80°, field of view (FOV) = 230 mm, voxel size = 2.4 × 2.4 × 3.6 mm, 32 contiguous 3.6-mm axial slices, 0-mm inter-slice gap]. Prior to each scan, seven volumes were discarded to allow T1-Equilibration effects. Within each functional run, the inter-trial intervals corresponding to the MR frames served as baseline or null events (i.e., fixation cross presented in the center of the screen). After the scanner upgrade, image acquisition at Site 2 ($N = 56$) was carried out using a 3T Prisma Fit MRI scanner equipped with a 64-channel head coil. Whole-brain functional images were acquired using a gradient-echo echo-planar pulse sequence [TR = 1250 ms, TE = 33.40 ms, FA = 45°, FOV = 220 mm, voxel size = 2.2 mm^3, 64 contiguous 2.20-mm axial slices, 0-mm inter-slice gap]. Prior to each scan, 11 volumes were discarded to allow T1-Equilibration effects. High-resolution T1-weighted anatomical images were collected at both sites with the same acquisition parameters: matrix size 256 × 256; 160 contiguous axial slices; voxel resolution 1 mm; TR = 2300 ms, TE = 2.98 ms, T1 = 900 ms; and FA = 9°.

fMRI Data Processing and Analyses. Imaging data were processed in two first level models using Analysis of Functional NeuroImages (Cox, 1996): one for speech processing, and one for print processing. First, outlier voxels were censored and time series data were despiked. Next data were corrected for slice timing, registered to the high-resolution anatomical scan, and transformed to MNI space, and corrected for motion. To minimize scanner differences, data were scaled to a mean of 100 and blurred to 6 mm FWHM. The final general linear models for each task included 6 motion parameters, and censored any volumes with framewise displacement above 0.5 mm. Participants were not considered for further analysis if over 40% of volumes were censored due to motion. Of the 68 participants who were entered into group-level analyses, an average of 7–8% of TRs were censored during each functional task. The number of volumes affected by motion was not correlated with children's language or literacy skills.

Group-Level Analyses. Data from each participant were entered into two general linear models: one for speech processing, and one for print processing. Participants' BOLD response for each block of word pairs was modeled using a canonical hemodynamic response function (HRF), and averaged to generate statistical images for word processing > rest contrasts. We used second-level GLM analyses to obtain group-level contrasts, controlling for scanner differences, participant age, maternal education, and familial risk of dyslexia. We examined these contrasts using independent sample *t*-tests for whole-brain activation at an FDR corrected threshold of $q = .01$, and a cluster threshold of 62 as recommended by 3dClustSim ($\alpha < 0.10$). A group-level intersect map of converging print- and speech-related activation was constructed with 3dcalc using the output of the group analyses, with a combined threshold of $q = 0.0001$, $\alpha < 0.01$.

Individual Co-Activation. Modeling after the Rueckl et al. (2015) analytic approach, we first calculated binary statistical maps revealing the number of voxels active above $p = .01$ during both the auditory and the visual task for each participant. We then conducted logical conjunction-and analyses to reveal the number of voxels that were significantly active for both speech and print at a stringent combined probability of $p = .0001$. To explore the convergence of print and speech processes in regions associated with language and literacy more specifically, we additionally calculated the number of co-active voxels in *a priori* regions of interest, namely the left STG/MTG and left fusiform gyrus (FG) regions. We additionally calculated the number of co-active voxels in the left IFG, an *a posteriori* region prompted by the extensive spatial convergence at the whole-group level. These regions of interest were defined using structural masks according to the MNI template implemented in AFNI. As is to be expected in such a young sample, we observed great variability in the extent of spatial co-activation in all of our regions of interest, ranging from 0 to several hundred co-active voxels. Because variance in brain activation across the sample resulted in a skewed distribution, we performed a square root transformation on the number of active voxels in the whole brain for each task, as well as the number of co-active voxels for speech and print in the whole brain, and in the left IFG, STG/MTG, and FG masks. These transformed metrics of activation and co-activation were entered into a structural equation model in Mplus 8.0 (Múthen and Múthen, 2017) and a hierarchical linear regression in SPSS.

Voxel-wise correlation. We used 3dTcorrelate in AFNI (Cox, 1996) to calculate the correlation coefficient between each subject's parameter estimates during auditory word and visual word processing. We focused on an *a priori* left MTG region of interest (MNI coordinates $x = -47$, $y = -62$, $z = 21$), identified by Rueckl et al. (2015) in their voxel-wise correlation analysis as a key example of print-speech convergence across four distinct languages in adults. We extracted the mean Pearson correlation value in a 5 mm sphere centered around these coordinates, and entered this value as a dependent variable in regression models.

3. Results

Language and Reading Skills. All 133 participants were typically-developing native speakers of English, with varied levels of exposure to other languages. Mean standard scores on assessments of vocabulary, oral comprehension, phonological awareness, morphological awareness, decoding, word reading, and reading comprehension were all within the normal range for 5–6 year old children (Table 1). We observed typical word reading ability for children in the first year of schooling (mean standard score = 95.76, SD = 12.81). 13% of our participants could only identify letters (e.g., *k*, *L*), and 72% could read high frequency monosyllabic words (e.g., *car*, *she*). The remaining 15% could read more complex words (e.g., *animal*, *become*). The associations between children's language and literacy skills are detailed in Table 2. Children with useable, high-quality neuroimaging data from both tasks were likely to be from a slightly higher socioeconomic status (mean years of maternal education = 17.4 vs. 16.8, $t(132) = 2.24$, $p < .05$). However, there were no significant differences in age, language proficiency, or reading ability between the children who were and were not included in fMRI analyses.

Table 1
Standard scores of language and literacy skills.

	Full sample ($N = 134$)		fMRI sample ($N = 68$)	
	Mean (SD)	Range	Mean (SD)	Range
Age	5.73 (0.34)		5.74 (0.34)	
Gender	75 boys/59 girls		33 boys/35 girls	
Nonverbal IQ	105.39 (14.61)	85–147	105.91 (14.54)	85–141
Receptive vocabulary	118.73 (13.21)	85–145	118.68 (13.20)	88–143
Expressive vocabulary	105.38 (12.91)	63–139	106.90 (11.46)	77–130
Oral comprehension	112.71 (13.48)	63–137	113.50 (13.96)	72–137
Morphological awareness [a]	8.52 (4.62)	0–20	8.37 (4.94)	0–20
Phonological awareness [b]	12.60 (5.65)	0–30	13.58 (6.16)	0–30
Decoding	100.12 (15.34)	53–133	102.24 (16.42)	53–133
Letter/word reading	95.76 (12.81)	66–150	97.26 (13.63)	66–150
Reading comprehension	101.45 (10.40)	71–136	102.97 (10.82)	71–136

[a] Raw score out of 25.
[b] Raw score out of 34.

We then conducted a confirmatory factor analysis of the full sample's behavioral language and literacy assessments (N = 133). We theorized that our behavioral measures of vocabulary, morphological awareness, and listening comprehension represented an underlying latent construct of LANGUAGE, while decoding, word reading, and reading comprehension measured a latent construct representing LITERACY. The model was a good fit for our data (RMSEA = .07, CFI = .97, TLI = .96, SRMR = .05). All observed variables had strong and significant loadings onto two specified factors with all standardized estimates ranging from 0.76 to 0.95, supporting the validity of these underlying constructs (Fig. 2).

fMRI Task Performance. During each neuroimaging task, children heard or saw 24 pairs of words in a blocked design and judged whether they were the same or different (e.g., *table* - *table* = same, *house* - *green* = different). Children performed with high accuracy on both experimental tasks. Paired sample *t*-tests revealed slightly higher performance during the spoken (mean 86.6%) than the written word matching task (78.5%; $t(67) = 4.10$, $p < .05$). This difference was expected, as children were all proficient English speakers, but were only just beginning to learn to read.

Regional Activation During Kindergarten Speech Processing. When listening to spoken words, participants engaged a canonical, adult-like auditory language processing network. Compared to rest, auditory word processing revealed peak activation in the left superior temporal gyrus with extensive bilateral activation in STG and MTG regions, extending into the bilateral IFG and insula. We also observed activity in the bilateral superior frontal (SFG) and medial frontal gyri, bilateral pre- and postcentral gyri, as well as cerebellar and subcortical regions (Fig. 1A, Table 3).

Regional Activation During Kindergarten Print Processing. When reading words, participants engaged a canonical literacy network. Compared to rest, visual word processing revealed peak activity in the right FG, extending bilaterally throughout middle occipital, inferior temporal and fusiform regions, as well as bilateral clusters in the STG/MTG. This analysis also revealed extensive bilateral prefrontal activation in the IFG, SFG, middle frontal (MFG) and medial frontal gyri, as well as cerebellar and subcortical regions (Fig. 1B, Table 3).

Co-active Brain Regions for Print and Speech. To uncover the shared cortical regions engaged during both print and speech processing,

Table 2
Partial correlations between language and literacy measures.

	1	2	3	4	5	6	7	8
1. Receptive vocabulary	–							
2. Expressive vocabulary	.73***	–						
3. Oral comprehension	.74***	.59***	–					
4. Morphological awareness	.52***	.42***	.62***	–				
5. Phonological awareness	.40***	.45***	.42***	.44***	–			
6. Decoding	.25**	.30***	.28*	.33***	.63***	–		
7. Letter/word reading	.19*	.21*	.17	.27**	.47***	.86***	–	
8. Reading comprehension	.20*	.21*	.20*	.33***	.48***	.76***	.83***	–

Note. Controlling for age and maternal education. *$p < .05$, **$p < .01$, ***$p < .001$.

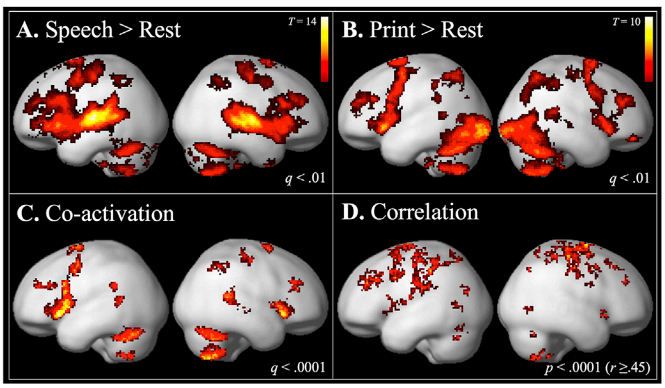

Fig. 1. Kindergarten brain activation for speech processing, print processing, and shared across modalities. Areas significantly activated during speech (A) and print (B) processing above an FDR cluster corrected threshold of $q < 0.01$, $k > 62$. Co-activation (C) presents the results of the conjunction-and analysis, revealing regions significantly activated during both print and speech processing. Correlation (D) reveals clusters of significantly correlated voxels ($r \geq 0.45$) during print and speech processing.

we conducted a whole-group intersect analysis. Results revealed that both auditory and visual word processing recruited frontal and temporal regions, including bilateral IFG/insula and bilateral STG/MTG, as well as the bilateral precentral gyrus and supramarginal gyrus extending into inferior parietal lobule (IPL; Fig. 1C). Additionally, both tasks engaged the bilateral anterior cingulate, MFG and SFG. Other overlapping clusters of activity were present in subcortical and cerebellar regions, detailed in Table 3.

Correlated Activity for Print and Speech. To uncover individual differences in the strength of brain activation for speech and for print, we used a voxel-wise correlation analysis to assess the relationship between the magnitude of print activation and the magnitude of speech activation. This analytic method provided more fine-grained information about the similarity in strength of activation for print and for speech. Results revealed clusters of significantly correlated voxels ($r \geq 0.45$, $p < .0001$) in bilateral frontal, temporal and parietal regions, including SFG/MFG, IFG, MTG and IPL (Fig. 1D). These voxel-wise correlations further support the notion of a widespread, shared network for both auditory and visual word processing, even at the onset of reading instruction.

Cognitive Abilities and Individual Print-Speech Co-activation. To quantify children's print-speech convergence, we first calculated the number of voxels that were significantly active during print processing and during speech processing. We then examined the extent of each child's print-speech co-activation in the whole brain, as well as in three anatomically defined regions of interest. The frontal (IFG) and temporal (STG/MTG) ROIs were selected because of their involvement in both print and speech processing in young readers (Chyl et al., 2018; Pugh et al., 2013; Shankweiler et al., 2008) as well as adults (Rueckl et al., 2015). The fusiform ROI was selected because of its rapid functional development during reading acquisition (Dehaene-Lambertz et al., 2018), and cross-modal involvement in auditory language tasks in children as young as 5 (Wang et al., 2018). These regions of interest were defined anatomically according to the MNI atlas implemented in AFNI (Cox, 1996). Similar to Preston et al. (2016), co-activation was defined as the number of voxels active above $p < .01$ during both tasks, resulting in a combined probability of $p < .0001$.

In order to examine the association between children's language and

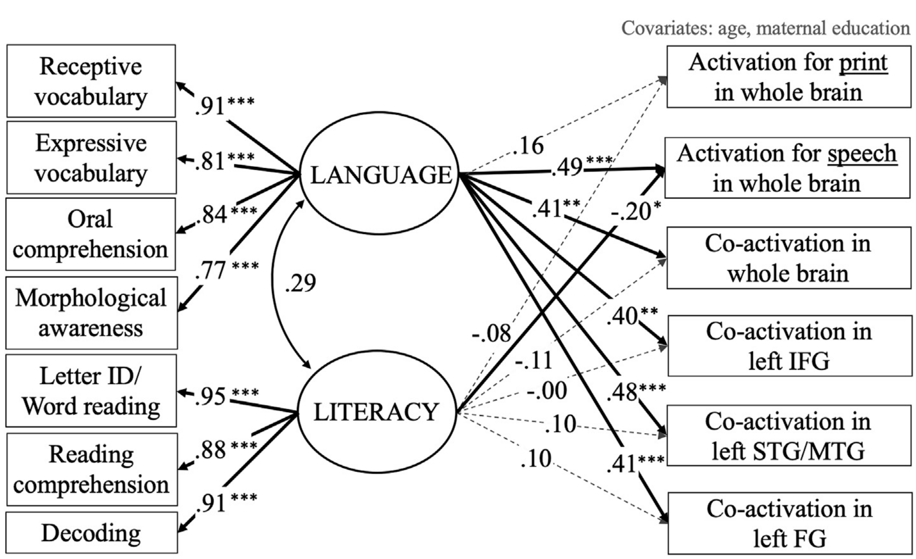

Fig. 2. Structural model explaining number of active voxels for print processing, speech processing, and print-speech co-activation in kindergarten. Solid lines indicate significant paths and dotted lines indicate non-significant paths. *$p < .05$, **$p < .01$, ***$p < .001$.

Table 3
Kindergarten brain activation specific to speech processing, print processing, and shared across auditory and visual modalities.

Regions	Peak MNI coordinates				Cluster size
	x	*y*	*z*	*Z*	Voxels
Speech Processing					
Bilat. STG, MTG, IFG, insula	−67	−13	7	7.03	19,262
Bilat. cerebellum (Crus I, VI), FG	−47	−59	−23	3.82	5,317
Bilat. superior/medial frontal, SMA, cingulate	−1	1	57	6.82	3,838
R pre/post central gyrus	43	−19	67	2.39	649
Bilat. lingual gyrus, cuneus	−3	−73	1	3.21	379
L cerebellum (VIII)	−23	−63	−61	3.76	342
R IPL	53	−55	53	3.21	181
L MFG/SFG	−35	45	35	3.15	141
L IPL	−61	−43	51	3.13	123
L cerebellum (IX)	−13	−53	−33	4.15	64
Bilat. cingulate gyrus	1	−29	27	3.03	64
Print Processing					
Bilat FG, ITG, MOG, cerebellum (Crus I, V)	45	−67	−21	4.22	11,742
Bilat. medial frontal, SFG, SMA, cingulate	−7	3	75	3.57	5,633
L thalamus, caudate, IFG, insula	−1	−13	13	2.6	4,877
R IFG, insula, thalamus, caudate	49	21	−9	3.57	1,867
R SPL/IPL	37	−63	59	3.78	1,856
L SPL/IPL	−27	−73	57	3.06	1,532
L cerebellum (VII, Crus 2)	−29	−77	−57	3.44	660
R MFG	43	43	31	3.36	448
R STG, MTG	51	−41	15	3.8	421
L MFG, SFG	−31	57	27	3.02	314
R lingual gyrus, cuneus	25	−63	5	3.34	211
L cuneus	−7	−75	13	4.09	145
Bilat. cingulate gyrus	1	−29	27	3.44	140
R pre/post central gyrus	37	−23	69	3.36	138
L MFG, IFG	−49	25	29	3.25	130
R hippocampus	31	−23	−9	3.42	118
L STG, MTG	−57	−51	13	3.78	98
L SMG/IPL	−61	−43	25	4.41	81
L hippocampus	−35	−21	−11	4.67	74
R SPL, precuneus	11	−71	51	3.02	67
	Center of mass				
Print-Speech Co-Activation	*x*	*y*	*z*		Voxels
Bilat. medial frontal, SFG, SMA, cingulate	0	13	49	–	3322
Bilateral cerebellum (VI, V, VIII)	2	−64	−25	–	3057
L insula, IFG	−42	16	7	–	1314
L thalamus, putamen	−13	−4	3	–	1236
R insula, IFG	39	21	1	–	645
R cerebellum (VIII)	30	−61	−52	–	637
R putamen	18	12	4	–	499
R STG, MTG	52	−37	9	–	328
L precentral gyrus, MFG	−46	−1	49	–	210
R thalamus	13	−15	9	–	169
L cerebellum (VI, VIII)	−34	−59	−52	–	154
R MFG, IFG	43	35	27	–	119
Right IPL	41	−53	46	–	117
R precentral gyrus	38	−21	57	–	112
L cuneus	−11	−75	11	–	85
L STG, MTG	−53	−50	10	–	84
R posterior cingulate, cuneus	13	−70	12	–	78
L SMG, IPL	−58	−44	27	–	75
L MFG	−34	41	28	–	69
L IPL	−47	−50	49	–	63

Note. Speech > Rest and Print > Rest clusters are FDR corrected, $q = 0.01$, extent threshold >62. Co-active clusters have a combined probability of $q = .0001$.
L, left hemisphere; R, right hemisphere. SFG, superior frontal gyrus; IFG, inferior frontal gyrus; MFG, middle frontal gyrus; SMA, supplementary motor area; STG, superior temporal gyrus; MTG, middle temporal gyrus; ITG, inferior temporal gyrus; SMG, supramarginal gyrus; IPL, inferior parietal lobule; SPL, superior parietal lobule; MOG, middle occipital gyrus; FG, fusiform gyrus.

literacy skills and their degree of print-speech convergence in kindergarten, we implemented the structural equation model (SEM) detailed in Fig. 2. This model assessed the contributions of language and literacy skill to the extent of brain activation during speech and print processing, as well as spatial co-activation. SEM analysis used full information maximum likelihood (FIML) conditions to maximize sample size and account for missing fMRI data not collected from the full sample. The final model controlled for participants' age and levels of maternal education. We established an excellent measurement model fit (RMSEA = .05, CFI = .98, TLI = .97, SRMR = .04).

Results of the SEM analysis revealed that the latent LANGUAGE factor was a significant positive predictor of the number of active voxels during speech processing ($\beta = .49$, $p < .001$), but not print processing ($\beta = .16$, $p = .23$). LANGUAGE additionally contributed to the number of co-active voxels for speech and print in whole brain ($\beta = .41$, $p = .001$), as well as the left IFG ($\beta = .40$, $p < .01$), STG/MTG ($\beta = .48$, $p < .001$) and FG regions ($\beta = .41$, $p < .001$). In contrast, the LITERACY factor was significantly associated with activation for speech ($\beta = -.20$, $p < .05$), and was *not* significantly associated with activation for print, or print-speech convergence in either region of interest (Fig. 2).

To further examine the cognitive abilities that may explain early print-speech convergence, we conducted two regressions. We extracted the mean correlation coefficient from an *a priori* region in the left MTG for each participant (Rueckl et al., 2015), and examined the extent to which language and literacy skill explained the correlation in activation for print and for speech. Our findings complement the results of our structural equation model. Kindergarten vocabulary, the observed variable with the strongest contribution to the LANGUAGE factor, explained significant unique variance in the MTG print-speech correlation above gender, age, maternal education and scanner differences (Table 4). In contrast, word reading ability, the strongest contributor to the LITERACY factor, was not associated with print-speech correlation (Supplementary Table 1).

Convergence Predicts Reading Outcomes. Finally, to better understand the relationship between print-speech convergence and reading acquisition, we conducted a longitudinal examination of 49 participants' print-speech co-activation in kindergarten (Time 1) and their literacy in Grade 1, one year later (Time 2; Supplementary Table 2). Regression results demonstrated that the number of co-active voxels for print and speech in the left STG/MTG accounted for a significant proportion of the variance in 1st grade reading outcomes, defined as a composite of word reading and reading comprehension, controlling for age at Time 1, scanner differences, and whole brain activity for print and speech (Table 5). Furthermore, the STG/MTG co-activation predicted unique variance in 1st grade reading above and beyond kindergarten word reading, measured by the Letter-Word Identification sub-test, indicating that this relationship is not driven by autoregressive effects (Table 6).

4. Discussion

This study compared the roles of spoken language proficiency and early reading skill in the development of 5–6-year-old children's neural organization for reading. Over the course of reading acquisition, children learn to recognize language in print, integrating the auditory and visual forms of language (Brem et al., 2010; Dehaene-Lambertz et al., 2018; Dehaene et al., 2015). How and when do spoken and written language processing converge? Our findings indicate that children's language proficiency shapes the extent of their print-speech convergence in kindergarten. Examined longitudinally, this kindergarten convergence predicts children's 1st grade reading proficiency. Our results demonstrate, for the first time, that spoken language proficiency explains significant variance in beginning readers' print-speech neural convergence. These findings extend our understanding of brain development for literacy at the onset of reading instruction, and suggest a developmental continuity from children's neural organization for spoken language processing to the gradual reorganization for reading.

Table 4
Multiple regression predicting print-speech correlation in MTG from oral language skill.

Predictor	β	t(62)	p
Scanner	-.15	−1.21	.229
Age	-.24	−1.85	.069
Gender	.04	.29	.772
Maternal education	-.09	-.75	.454
Oral language (Vocabulary)	.39	3.02	.004

Note. The model accounts for a significant amount of variance, $r^2 = 0.18$, $F(5,62) = 2.53$, $p = .038$. Vocabulary is measured using PPVT.

Table 5
Multiple regression predicting 1st grade reading from kindergarten print-speech Co-activation.

Predictor	β	t(47)	p
Scanner	-.13	-.91	.370
Age at Time 1	.11	.81	.424
Whole-brain activation to speech	-.06	-.32	.751
Whole-brain activation to print	-.27	−1.26	.241
Print-speech co-activation in left STG/MTG	.65	3.42	.001

Note. The model accounts for a significant amount of variance, $R^2 = 0.26$, $F(5,42) = 2.98$, $p < .05$. Print-speech co-activation refers to the number of voxels significantly active during both auditory and visual word processing in the left STG and MTG. 1st grade reading is a composite of single word reading and reading comprehension.

Table 6
Multiple regression predicting 1st grade reading from kindergarten word reading and print-speech Co-activation.

Predictor	β	t(48)	p
Kindergarten word reading	.58	5.27	<.001
Print-speech co-activation in left STG/MTG	.27	2.45	.018

Note. The model accounts for a significant amount of variance, $R^2 = 0.48$, $F(2,46) = 21.17$, $p < .001$. Print-speech co-activation refers to the number of voxels significantly active during both auditory and visual word processing in the left STG and MTG. 1st grade reading is a composite of single word reading and reading comprehension.

What is the nature of the emerging literacy network in the first year of formal schooling, as children learn to recognize language in print? Proficient readers across languages and orthographies reciprocally engage visual regions of the brain during spoken word processing (Price, 2012) and auditory language regions during visual word processing (Bolger et al., 2005). In the superior temporal sulcus (STS) specifically, proficient readers' responses to spoken and written language are virtually indistinguishable (Wilson et al., 2018). This cross-modal integration of auditory and visual language processing begins to emerge at the onset of learning to read. For example, specificity in 5–6-year-olds' occipito-temporal response to auditory phonological analyses – the early engagement of visual regions during spoken language processing – is related to their reading proficiency (Wang et al., 2018). However, while recent work has illuminated both the universality of print-speech convergence in proficient readers (Rueckl et al., 2015), and its importance for successful literacy acquisition (Preston et al., 2016), *how* and *when* this convergence develops has remained an open question.

In this study, we took two approaches to examine print-speech convergence in beginning readers. First, we used conjunction-and logic to uncover the shared cortical regions engaged during both print and speech processing. This analysis revealed robust print-speech co-activation in bilateral IFG, STG, MTG, and inferior parietal regions, as well as the cerebellum and subcortical areas. These findings align with co-activation previously observed with older and more proficient readers (Frost et al., 2009; Preston et al., 2016; Shankweiler et al., 2008). Second, we used a voxel-wise correlation analysis to examine the cortical regions that behave similarly during print and speech processing. This complementary analysis provides unique information about individual differences in the strength of regional activation and the similarity between auditory and visual word processing. Our findings revealed highly correlated activation for print and speech in bilateral frontal, temporal and parietal regions, replicating recent work with adults (Rueckl et al., 2015). Together, these two distinct methods provide the most complete picture to date of the converging print-speech network for literacy in beginning readers. While research suggests that print-speech convergence is universal among adult readers (Rueckl et al., 2015), we provide new evidence to suggest a striking degree of similarity and overlap in spoken and written word processes in the early stages of reading acquisition.

At the core of our inquiry was the role of spoken language processing in shaping the brain's emerging literacy network. We defined spoken language as a latent construct comprised of receptive and expressive vocabulary, oral comprehension and morphological awareness. Taken together, this LANGUAGE measure explained significant variance in the number of voxels that kindergarteners activated during spoken word processing, but not during written word processing. Structural equation modeling further revealed that LANGUAGE was strongly associated with spatial co-activation for print and speech in inferior frontal, superior temporal and fusiform regions. In other words, better oral language proficiency was related to greater overlap in brain activation across spoken and written word processing, a signature of a more convergent network. Voxel-wise correlation analyses yielded complementary findings. In particular, the regression analyses showed that children's vocabulary knowledge, the strongest contributor to the LANGUAGE latent factor, explained unique variance in the strength of voxel-wise correlation in the left MTG region. Thus, kindergarten language ability was significantly associated with print-speech spatial co-activation and the extent to which children similarly engage critical regions for both print and speech processing. Together, these analyses suggest that beginning readers' print-speech convergence is shaped by their spoken language proficiency.

In contrast to the strong association between oral language skill and neural convergence, we found no direct association between early literacy skill and either print-speech correlation or co-activation in beginning five-year-old readers. We defined LITERACY as a latent construct comprised of kindergarten decoding, single-word reading and passage comprehension behavioral assessments. The LITERACY variable significantly contributed to children's neural activation for speech, perhaps revealing an emerging reciprocal relationship between spoken and written language processing. However, LITERACY was not associated with the number of voxels activated during word reading, or the number of co-active voxels in the whole brain, IFG, STG/MTG or FG. Furthermore, word reading ability, the strongest contributor to the LITERACY factor, did not explain the voxel-wise correlation across modalities.

The lack of a significant association between children's early reading ability and their print-speech convergence in our sample of beginning kindergarten readers complements prior findings and deepens our understanding of the emergence of print-speech neural convergence. In particular, Chyl et al. (2018) recently conducted two separate co-activation analyses to compare a sample of pre-readers with age-matched readers, who could read an average of 21 words in 1 minute. Their results revealed print-speech convergence in left inferior frontal and superior temporal regions among readers, but not among pre-readers. Our study builds upon this discovery by examining reading proficiency in *emergent* readers who fall in between Chyl's two groups in their reading proficiency, ranging from letter knowledge to rudimentary word reading ability. By modeling the relation between language proficiency, reading skill, and print-speech convergence across a range of emergent reading ability, we extend the prior literature by illuminating the transition from pre-reader to reader at the start of schooling. Our findings may indicate that the relation between orthographic knowledge and neural activity emerges over the course of reading acquisition, thus becoming apparent in more sophisticated readers.

While reading skill in kindergarten did not explain variance in children's print-speech convergence, longitudinal examination revealed that print-speech convergence significantly predicted children's future reading skill in 1st grade over and above the contribution of kindergarten single word reading. This finding extends prior work with older children, which revealed that print-speech co-activation can predict reading outcomes two years later (Preston et al., 2016). Taken together with prior findings, we can now offer a more complete view of the neurodevelopmental trajectory for reading, and the importance of print-speech convergence in successful literacy acquisition.

The central discovery in the present study is that spoken language proficiency shapes the emergence of spatial co-activation for speech and print in the early stages of learning to read. This finding is striking given the relationship between print-speech convergence and growth in literacy skill later in development (Preston et al., 2016). Indeed, we find that the extent of children's co-activation in kindergartener is predictive of reading acquisition outcomes one year later, and possibly beyond. However, while print-speech spatial co-activation may indeed emerge as a function of learning to read (Chyl et al., 2018), behavioral measures of early reading skill do not explain the extent of children's neural convergence for print and speech at the onset of literacy acquisition. Put another way, convergence may predict literacy, but it is oral language proficiency that predicts convergence. These results extend prior work demonstrating the strong relationship between auditory language processing and future reading success (Leppänen et al., 2011; Raschle et al., 2014; Raschle et al., 2012), and suggest a developmental mechanism by which spoken language proficiency and auditory word processing may form the foundations of the reading network.

Questions remain about what cognitive or perceptual mechanisms explain brain activity during visual word processing for the beginning readers in our sample, providing a promising avenue for future research. Our inquiry would have been further strengthened had more children completed both the behavioral and neuroimaging components. This limitation was addressed by analyzing our data under FIML conditions, maximizing the effective sample size (Enders, 2010). Furthermore, in spite of the missing data, this is a relatively large sample compared to much of the prior research using fMRI, and contributes new and valuable insight to the field.

Our findings reveal the relationship between spoken language abilities and the emergence of the print-speech neural convergence in beginning 5-year-old readers. In proficient adults, successful literacy has been linked to the neurocognitive integration of language across auditory and visual forms. We find evidence of such convergence in 5-year-old beginning readers. Critically, variability in early print-speech convergence is explained by spoken language proficiency, and in turn predicts children's reading abilities over time. By revealing the early engagement of the language network in beginning readers, our findings bridge the theoretical understanding of reading acquisition as being simultaneously driven by continuity in children's spoken language development, and discontinuity in the emergence of new literacy skills.

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Data availability statement

De-identified neuroimaging data and preprocessing scripts will be made available on the Deep Blue Data public repository (https://deepblue.lib.umich.edu/data).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2019.116021.

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