The relation of home literacy environment to brain specialization and sensitivity for phonological and semantic processing of spoken words

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Abstract

Purpose: Neural specialization is a developmental phenomenon across multiple domains of language processing. The home literacy environment (HLE) is observed to relate to brain activation during language and reading tasks; however, whether HLE relates to phonological and semantic functional specialization and sensitivity remains unknown.

Method: Using an open-source dataset, the present study examined 33 5–6-year-olds and 76 7–8-year-olds. Data from fMRI sound and meaning judgment tasks were used to examine phonological and semantic functional specialization (contrasting tasks) and sensitivity (comparing conditions within a task). Then, voxel-wise regression analyses were used to test correlations between those brain indexes and HLE (i.e., family-to-child reading, child independent reading) measured using a parent survey.

Results: We observed weak evidence of phonological specialization at 5 years old and weak evidence of semantic specialization at 7 years old associated with family-to-child reading. We also observed weak evidence of phonological sensitivity at 5 years old and strong evidence of semantic sensitivity at 7 years old associated with family-to-child reading. Across the cohorts, a progression from temporal to frontal brain regions was observed in those relations, in line with prior literature on language specialization and sensitivity across development.

Conclusions: Overall, our results suggest that HLE is linked to functional specialization and sensitivity, with a relation of family-to-child reading to processing the sound structure of language at 5 years old and meaning at 7 years old. This finding supports the Interactive Specialization theory, which emphasizes the role of environmental inputs in neural specialization.

Keywords

home literacy environment, phonology, semantics, functional specialization, shared reading

Introduction

According to the Interactive Specialization theory (Johnson, 2011), brain cortices start with broad functionality and then become selective to narrower functions as children develop, alongside skill acquisition and environmental exposure, which is a process that is referred to as functional specialization. Developmental disorders are often associated with atypical or delayed specialization (Johnson, 2011). Thus, understanding how and why children develop their brain specialization is key to helping children with developmental disorders. Language processing and reading are skills developed from a young age that can influence a variety of important life factors such as academics, career success, and overall well-being (Gross, 2006). However, how neural specialization and sensitivity occur for semantic and phonological processing, two basic components for spoken language processing and subsequent reading acquisition, remain unclear (Frost et al., 2005; Wang et al., 2020).

Prior work (Weiss et al., 2018; Wang et al., 2021) has investigated brain specialization and sensitivity for semantic and phonological processing using a sound judgment and a meaning judgment task across developmental stages, with the following operations. Specialization analyses entail comparing activation during two different types of tasks whereas sensitivity analyses entail comparing which areas are engaged during a more challenging condition compared to a less challenging condition within the same type of task (also known as parametric manipulation; Wang et al., 2021). Using two language processing tasks allow us to see which brain areas are specialized for phonology vs. semantics. Furthermore, having parametric manipulations within each of those tasks allows us to see which areas are sensitive to within-task differences. Although brain specialization and sensitivity reflect different constructs, brain regions showing sensitivity to difficulty levels are likely localized in highly specialized areas. By studying 5- to 6-year-old children, Weiss et al. (2018) observed that young children exhibited phonological and semantic specialization and sensitivity only in temporal brain regions. Specifically, the left posterior superior temporal gyrus (pSTG) showed greater activation for the sound than meaning judgment tasks, and greater activation for the harder than easier conditions within the sound judgment task. In contrast, the left posterior middle temporal gyrus (pMTG) showed greater activation for the meaning than the sound judgment tasks and greater activation for the harder than easier conditions within the meaning judgment task. In a subsequent study using the same tasks with older children, Wang et al. (2021) observed that 7- to 8-year-old children exhibited phonological and semantic specialization and sensitivity in both the frontal and temporal brain regions. Specifically, the left dorsal inferior frontal gyrus (dIFG) and the left pSTG (although pSTG was only evident in specialization when a more liberal statistical threshold was applied) were more active for the sound than meaning judgment tasks, and greater activation for the harder than easier conditions within the sound judgment task. In contrast, the left ventral IFG (vIFG) and the left pMTG showed higher activation for the meaning than sound judgment tasks, with the former region also exhibiting greater activation for the harder than easier conditions within the meaning judgment task. These findings from 7- to 8-year-old children are similar to those from studies on adults (Booth et al., 2006), suggesting that 7- to 8-year-olds have already begun to show adult-like phonological and semantic specialization during spoken word processing. Moreover, different findings in Weiss et al. (2018) and Wang et al. (2021) suggest that these specializations and sensitivity appear earlier in the temporal than the frontal cortex.

Although we now know that semantic and phonological specialization and sensitivity evolve in children ages 5 year and older, what contributes to that brain development remains unclear. A stimulating learning environment is a critical factor supporting the development of a child's cognitive abilities and educational outcomes. In the early years, language input is aural, later supplemented by written forms when literacy instruction begins at school (Hulme et al., 2020). Indeed, mounting evidence indicates that the home literacy environment (HLE), including parental literacy, access to books, interactions with adults in reading activities, and/or exploration of print by children on their own, is one of the predictors of early language and reading skill development (Mol & Bus, 2011; Niklas et al., 2020; Sénéchal & LeFevre, 2014). The importance of HLE to the development of specific components of language processing was further underscored by the findings in behavioral studies that HLE was associated with phonological awareness (Niklas & Schneider, 2013) and vocabulary skills (Frijters et al., 2000; Sénéchal & LeFevre, 2014). Although in school-age children, HLE can be composed of both maternal and independent reading, these were observed to be intercorrelated, with the former predicting the latter. Only maternal teaching of reading at preschool predicted children's first-grade reading skills (Silinskas et al., 2020). However, how parental and independent reading are separately related across development to phonological and semantic skills for spoken words remains understudied.

Like behavioral studies, research using functional magnetic resonance imaging (fMRI) has also suggested a relation between HLE and brain activity for language or reading (see Hutton et al., 2021 for review). For example, Hutton et al. (2015) found that 3- to 5-year-old children with greater home reading exposure exhibited more robust activation within the language network, including the MTG, while listening to stories. Powers et al. (2016) observed that in a group of children around 5.5 years old, HLE is associated with brain activation in areas including the left IFG and STG during a phonological awareness task. Furthermore, when comparing children with and without a familial risk of dyslexia, those without showed stronger relations between HLE and areas including the IFG whereas those with a familial risk showed stronger relations with the right precentral gyrus compared to children with a familial risk, suggesting a differential relationship between HLE and brain activation in children with and without a genetic predisposition for dyslexia. Girard et al. (2021) showed that the frequency of reading activities of 8-year-old children at home was positively correlated with their neural adaptation to the repetition of printed words in the IFG. Horowitz-Kraus et al. (2023) summarized their observation of multiple neural studies showing the utilization of neural systems associated with executive functions, language, and visual processing during story-listening, and their positive relation to subsequent reading skills, which upheld the American Association of Pediatrics recommendation to read to children starting from birth (Pediatrics, 2014).

Although previous work highlighted the linkage between HLE and brain activation during one language or reading task (Hutton et al., 2015; Powers et al., 2016; Girard et al., 2021), nothing is known about the relations between HLE and the neural specialization and sensitivity for different linguistic components (i.e., phonology and semantics) during spoken language processing. The current study aimed to address this gap by investigating the relation of a child's HLE to phonological and semantic specialization and sensitivity by using the same fMRI tasks as in Weiss et al. (2018) and Wang et al. (2021). This work builds on prior literature on phonological and semantic specialization and sensitivity in developing children (Weiss et al., 2018; Wang et al., 2021) and directly addresses a core hypothesis from the Interactive Specialization model where the effects of environmental inputs on neural specialization are emphasized.

Components of HLE may demonstrate different relations with children’s literacy skills (Silinskas et al., 2020). Thus, we separately examined the relations of language specialization and sensitivity to two aspects of HLE: 1) the frequency or amount of time a child is read to by an adult (family-to-child reading) and 2) the frequency or amount of time a child reads to themself or others (child independent reading). However, due to limited work on this relation in school-age children, we did not preregister different predictions for the relations of family-to-child reading and child independent reading to brain specialization and sensitivity.

We generated our specific hypotheses in pre-registration. For 5- to 6-year-old children, we predicted that both components of HLE would be positively correlated with the strength of phonological specialization and sensitivity in the left pSTG. Additionally, both components of HLE would be positively correlated with the strength of the semantic specialization and sensitivity in the left pMTG. For 7- to 8-year-old children, we predicted similar relations to 5-to-6-year-olds in temporal cortex, but additionally predicted that the relation of HLE to phonological specialization and sensitivity would extend to the left dIFG and that the relation of HLE to semantic specialization and sensitivity would extend to the left vIFG. We also predicted the relation of HLE to be stronger in younger groups in the temporal compared to the frontal cortex due to the delayed occurrence of specialization and sensitivity in the frontal lobe observed in previous studies (Wang et al., 2021; Weiss et al., 2018).

Method

This study used part of an existing dataset that is shared on OpenNeuro.org. Detailed information about the dataset can be found in the data descriptor by Wang et al. (2022). The research questions, hypotheses, and analytical plan were preregistered (see study plan on 5-6-year-olds https://osf.io/d9cxm and study plan on 7-to-8-year-olds https://osf.io/xrgtu). The analyses for the 7- to 8-year-old age group were preregistered first because that group has a larger number of participants and then the analyses for the 5- to 6-year-old age group were preregistered. However, in this paper, we report the analyses and results according to chronological age. The list of participants and runs used in the current study as well as the code used to analyze the data were shared on https://github.com/comptoab/HLE_PhonSem_Specialization.

Participants

Forty-six 5- to 6-year-old children who completed two full runs of the two experimental fMRI tasks and had complete HLE and socioeconomic status (SES) data were screened in this study for the younger cohort. Nine participants were excluded after screening for movement during the fMRI tasks (see "Preprocessing" section for criteria), two were excluded due to low in-scanner task accuracy (see "In-scanner tasks" section for criteria), and one due to excessive signal distortions on the fMRI image. One participant was excluded due to left-handedness. Thus, 33 children (21 females, mean age = 5.9, SD = 0.3, range = 5.5 to 6.6 years old, 88% White) were included in the final sample as the younger cohort. This paper uses the same open data set as this prior work, but the group of participants from that dataset differs slightly from our paper, given the exclusionary criteria for this project. For the 5–6-year-old participants, our fMRI inclusionary criteria differed from Weiss et al. (2018) so only 21 of our 33 participants overlap with the sample presented in their paper. One-hundred and ten 7- to 8-year-old participants reported as a final sample in the study of Wang et al. (2021) were screened in this study as the older cohort. Specifically, our 7–8-year-old participants are a subset of the participants used in Wang et al. (2021) including only those with home literacy data.

Thirty-four children did not have HLE and SES data completed and were excluded from further analyses. Thus, 76 participants (47 females, mean age = 7.5, SD = 0.3, range = 7.1 to 8.4 years old, 83% White) were included in the final sample as the older cohort. To calculate age, the participant's age across all four of their fMRI runs used in the analysis was averaged in the 5–6-year-olds or in the 7–8-year-olds. Participants could be invited for scanning on additional days if they had not finished the four functional tasks (Wang et al., 2022). Included participants averaged 1.4 months between first and last scan date. Exclusionary criteria were evaluated at each time point in the dataset. A total of 12 participants were included in both the younger and older cohorts; however, given this small amount of data, longitudinal analyses were not conducted. In the dataset, there is a gap in age between the groups, so the data should not be treated as one continuous group across ages.

Wilcoxon rank tests were performed to compare HLE of the groups that were included and excluded from analyses. There was no significant difference in family-to-child (p = .262) or child independent reading (p = .257) in the younger age group. The older age group did not significantly differ in terms of family-to-child reading (p = .050) but did differ in terms of child independent reading (p = .006), such that those included in analyses read to themselves more often than those excluded from analyses.

Parents or guardians of the younger and older children were asked to complete an exclusionary survey and a Developmental History questionnaire. For both groups, SES score measured as maternal education (highest degree completed) was extracted from the Developmental History questionnaire. For the younger group, HLE scores were extracted from the Developmental History questionnaire, measuring (a) family-to-child reading: amount of time a child is read to by a family member each day ["How long per day is your child read to by an adult?" (0-15 minutes; 15-30 minutes; 30-60 minutes; More than 1 hour per day; More than 2 hours per day)]; and b) child independent reading: amount of time a child reads to themself or others each day ["How long per day does your child read on his or her own? (if your child does not read yet, please select 0-15 minutes)" (0-15 minutes; 15-30 minutes; 30-60 minutes; more than 1 hour per day; more than 2 hours per day)]. For the older group, a Cognitive Stimulation survey, with questions adapted from parent interview questions from the Early Childhood Longitudinal Studies (ECLS) program (Tourangeau et al., 2004), was implemented including HLE scores measuring (a) family-to-child reading: frequency with which a child is read to by a family member each week ["In a typical week, how often do you or any other family members read books to your child in English?" (Not at all; Once or twice a week; 3-6 times a week; Every day)]; and b) child independent reading: frequency with which a child reads to themself or others outside of school ["In the past week, how often did your child read to himself/herself or to others outside of school?" (Never; Once or twice a week; 3-6 times a week; Every day)]. These reading practices for participants included in analysis can be found in Table 1. Histograms illustrating the distribution of responses for the HLE questions of included participants are available in Supplementary Figure S1.

Table 1

Reading Practices

Covariate	**Description**	**Median (IQR, range)**
	Younger cohort	
Family-to-Child Reading	"How long per day is your child read to by an adult?" (0-15 minutes; 15-30 minutes; 30-60 minutes; More than 1 hour per day; More than 2 hours per day)	2(1, 1-4)
Child Independent Reading	"How long per day does your child read on his or her own? (if your child does not read yet, please select 0-15 minutes)" (0-15 minutes; 15-30 minutes; 30-60 minutes; More than 1 hour per day; More than 2 hours per day)	2 (1, 1-5)
	Older cohort	
Family-to-Child Reading	In a typical week, how often do you or any other family members read books to your child in English?" (Not at all; Once or twice a week; 3-6 times a week; Every day)]	3 (1.25, 1-4)
Child Independent Reading	"In the past week, how often did your child read to himself/herself or to others outside of school?" (Never; Once or twice a week; 3-6 times a week; Every day)	4 (1, 1-4)

Note. The table displays reading practices for the younger (5-6-year-olds) and older (7-8-year-olds) cohort. IQR: interquartile range.

Children were asked to complete several screening tests. Participants from the younger and older cohorts were included if they met the criteria reported by Wang et al. (2021). The following inclusionary criteria were implemented: (a) right-handedness, defined as completing at least 3 of the 5 handedness tasks with the right hand (write, draw, pick up, open, and throw); (b) speaking Mainstream American English (MAE) as measured by the diagnostic evaluation of language variation (DELV; Seymour et al., 2003), Part 1 Language Variation Status sub-test. Children's scores were categorized as MAE based on the manual for this test for each of the age groups: 7 out of 15 responses for 5-year-olds, 8 out of 15 responses for 6-year-olds, 9 of 15 responses for 7-year-olds and 11 of 15 responses for 8-year-olds. One 5-year-old participant scored 6 and thus was classified as showing some variations from MAE. However, this participant met all of the other inclusionary criteria, had 89% accuracy in the phonological in-scanner task and 63% accuracy in the semantic in-scanner task (across all lexical and perceptual conditions; see "In-scanner tasks" section below) and thus was included in the study; (c) no neurological, psychiatric or learning disorders, according to the developmental history questionnaire; and (d) typical hearing and typical or corrected-to-normal vision, as reported by a parent or guardian. Additionally, to assess participants' non-verbal IQ and language skills, a series of standardized tests were administered. Nonverbal IQ was measured using the Kaufman Brief Intelligence Test, Second Edition (KBIT-2, Kaufman & Kaufman, 2004). General language skill was measured using the Core Language Scale (CLS) score on the Clinical Evaluation of Language Fundamentals, Fifth Edition (CELF-5, Wiig et al., 2013). All children included in the study had normal IQ, as indexed by a standardized score of 80 or higher on the KBIT-2, and typical language abilities, as indexed by a standardized CLS score of 80 or higher on the CELF-5. One child whose data was included at age 5 did not have a KBIT-2 score for that session but had a KBIT-2 score at their age 7 session that was above 80. All children also completed standardized assessments of semantics, measured using CELF-5 Word Classes subtest, and phonological awareness, measured using the Comprehensive Test of Phonological Processing (CTOPP-2) Elision subtest (Wagner et al., 2013). Information on demographics and nuisance covariates is displayed in Table 2.

Table 2

Demographics

Nuisance Covariate	**Description**	**Mean (SD, range)**	
		Younger cohort	Older cohort
Age	Average of participant age in months across all four runs	71.1 (3.1, 66–79)	90.3 (3.6, 85.5–101)
Phonology in-scanner task performance	Mean accuracy score (%) across both runs in the sound judgment task (Rhyme & Onset)	71.8 (12.5, 45.8-91.7)	79.4 (9.3, 50.0-93.8)
Semantics in-scanner task performance	Mean accuracy score (%) across both runs in the meaning judgment task (High & Low)	78.6 (11.4, 54.2-97.9)	86.7 (8.7, 58.3-100.0)
		Median (IQR, range)	
Socioeconomic Status (SES)	Highest grade/degree completed by mother with 1 “High School,” 2 “Some College,” 3 “Associate Degree,” 4 “Bachelor’s Degree,” and 5 “Master’s Degree or higher”	4 (1, 1-5)	4 (0, 1–5)

Note. The table displays demographic (age, socioeconomic status) and task performance (sound and meaning) for the younger (5-6-year-olds) and older (7-8-year-olds) cohort. SD: standard deviation, IQR: interquartile range.

Participants were recruited in the Austin, Texas metropolitan area. Exclusionary criteria for the project included that participants could not spend more than 40% of their time speaking a non-English language (see Wang et al., 2022 for a full description). For the sample used in this study, in total 21% of the 5-6-year-old age group identified as Hispanic or Latino. In total 88% of participants in the 5-6-year-old age group identified as White, 9% identified as Black or African American, and 3% identified as multiracial. In total 16% of the 7-8-year-old age group identified as Hispanic or Latino. In total 83% of participants in the 7-8-year-old age group identified as White, 3% as Black or African American, 12% as multiracial, 1% as Asian, and 1% as American Indian or Alaskan Native. All the experimental procedures were approved by the Institutional Review Board (IRB) of the University of Texas at Austin (IRB Protocol Number 2014-07-0018). Informed consent was collected from participants' parents or guardians and assent was collected from children before participation in the study.

Experimental tasks and procedure

In-scanner tasks

We employed experimental tasks previously used in studies of 5- to 6-year-old children (Weiss et al., 2018) and 7- to 8-year-old children (Wang et al., 2021). In the sound judgment task, tapping into phonological processing for spoken words, children were auditorily presented with two sequential one-syllable words and asked to determine whether the two words share any of the same sounds. The task included two related experimental conditions in which pairs of words shared the onset or the rhyme, and one unrelated experimental condition in which presented words did not share any of the sounds (see Table 3 for examples). Participants used the right index finger for a "yes" response (the two words share an onset or rhyme) and the right middle finger for a "no" response (the two words do not share any of the sounds).

The experimental conditions were designed according to the following standards. For the Onset condition, two words shared the same initial phoneme (corresponding to one letter of their written form). For the Rhyme condition, the word pairs shared the same final vowel and phoneme or cluster (corresponding to 2 to 3 letters at the end of their written form). In the Unrelated condition, there were no shared phonemes or letters of its written form. All words were monosyllabic, and all word pairs were not associated semantically based on the University of South Florida Free Association Norms (Nelson et al., 2004). Linguistic characteristics of stimuli were obtained from the English Lexicon Project (https://elexicon.wustl.edu/, Balota et al., 2007). Conditions did not significantly differ in word length, the number of phonemes, written word frequency, orthographic, phonological and semantic neighbors, nor the number of morphemes for either the first or the second word in a trial within a run (Rhyme vs. Onset: ps > .123; Rhyme or Onset vs. Unrelated: ps > .123) or across runs (Rhyme: ps > .162; Onset: ps > .436; Unrelated: ps > .436). There were also no significant differences between conditions in phonotactic probabilities (obtained from a phonotactic probability calculator https://calculator.ku.edu/phonotactic/English/words,Vitevitch & Luce, 2004), including phoneme and bi-phone probabilities for either the first or the second word in a trial either within a run (Rhyme vs. Onset: ps > .400; Rhyme or Onset vs. Unrelated: ps > .456) or across runs (Rhyme: ps > .068; Onset: ps > .225; Unrelated: ps > .206). In addition to three experimental conditions – Onset, Rhyme, and Unrelated – the task included a perceptual control condition in which children heard two sequentially presented frequency-modulated sounds (i.e., “shh-shh”) and were asked to press the “yes” button.

In the meaning judgment task, examining children's semantic processing for spoken words, children were auditorily presented with two sequential one-syllable words and asked to judge whether the two words go together semantically. The semantic association between word pairs was either high, low, or the two words were unrelated in their meaning (see Table 3). Participants used the right index finger for a "yes" response when pairs of words had high or low semantic association, and the right middle finger for a "no" response when the two words were semantically unrelated. Associative strength was derived from Forward Cue-to-Target Strength (FSG) values reported by the University of South Florida Free Association Norms (Nelson et al., 2004). The High association condition was defined as word pairs having a strong semantic association with an association strength between 0.40 and 0.85 ($M = 0.64$, $SD = 0.13$). The Low association condition was defined as word pairs having a weak semantic association with an association strength between 0.14 and 0.39 ($M = 0.27$, $SD = 0.07$). The Unrelated condition was defined as word pairs that shared no semantic association. There were no significant differences in association strength between the two runs of the meaning judgment task ($ps > .425$). As for the sound task, there were also no significant differences between conditions in word length, number of phonemes, number of syllables, written word frequency, orthographic, phonological and semantic neighbors, nor the number of morphemes for either the first or the second word in a trial either within runs (High vs. Low: $ps > .167$; High or Low vs. Unrelated: $ps > .068$) or across runs (High: $ps > .069$; Low: $ps > .181$; Unrelated: $ps > .097$; linguistic characteristics were obtained from the English Lexicon Project https://elexicon.wustl.edu/, Balota et al., 2007). In addition to three experimental conditions – High, Low, and Unrelated – the task included a perceptual control condition as described above.

Participants completed two runs of each of the tasks with 12 trials per condition per run for a total of 24 stimuli for each of the four conditions. Both tasks included a total number of 96 trials divided into two separate 48-trial runs. The duration of each auditory word ranged from 439 to

706 ms in the sound task and 500 to 700 ms in the meaning task. The second word was presented 1,000 ms after the onset of the first word. In the sound task, the overall stimuli duration (the two words with a brief pause in between) ranged from 1,490 to 1,865 ms and was followed by a jittered response interval ranging from 1,500 to 2,736 ms. In the meaning task, the overall stimuli duration ranged from 1,500 to 1,865 ms, and was followed by a jittered response interval ranging from 1,800 to 2,701 ms. A blue circle appeared simultaneously with the auditory presentation of the stimuli to help maintain attention on the task. It then changed to yellow to provide 1,000 ms for the participants to respond if they had not already done so, before moving on to the next trial. The total trial duration ranged from 3,000 to 4,530 ms in the sound task and 3,300 to 4,565 ms in the meaning task. Each run lasted ~3 min. To make sure that the participants were acclimated to the scanner environment and familiarized with all the instructions, prior to the fMRI scanning session all children completed sound and meaning tasks on a computer and in a mock scanner.

To ensure that participants included in the final analysis were engaged in and capable of performing the tasks, they had to score ≥ 50% on the perceptual and Rhyme or High condition. To ensure that there was no response bias during the tasks, participants included in the final analysis had to have an accuracy difference between the Rhyme or High condition (requiring a "yes" response) and the Unrelated condition (requiring a "no" response) of < 40%. Participants who did not score within an acceptable accuracy range or had response bias on the fMRI tasks were excluded from the final analysis. The final mean, SD, and range of the accuracies of two runs for each condition during the sound and the meaning judgment tasks for the younger and older cohorts are displayed in Table 4. For participants in the 7–8-year-old age group, the same runs used in Wang et al. (2021) were used for analysis. For these participants, if a participant completed repeated runs that met inclusionary criteria, the best run was chosen first based on least movement and then based upon highest accuracy across all task conditions. For participants in the 5–6-year-old age group, if a participant completed repeated runs that met inclusionary criteria, behaviorally and in terms of movement, the run with the highest accuracy across the experimental task conditions (i.e., Onset, Rhyme, and Unrelated for the sound task and Low, High, Unrelated for the meaning task) was used for analysis.

Table 3

Task Stimuli Conditions

Task	Condition	Response	Brief Explanation	Example
Sound task	Onset	Yes	Two words share the first sound (consonant)	Coat-cup
	Rhyme	Yes	Two words share the final sound (vowel + last consonant)	Wide-ride
	Unrelated	No	Two words do not share sounds	Zip-cone
	Perceptual	Yes	Two frequency-modulated sounds	Shh-shh
Meaning task	Low	Yes	Two words weakly associated in their meaning	Save-keep
	High	Yes	Two words strongly associated in their meaning	Dog-cat
	Unrelated	No	Two words no associated in their meaning	Map-hut
	Perceptual	Yes	Two frequency-modulated sounds	Shh-shh

Note. The table displays stimuli conditions and examples for sound and meaning judgment tasks.

Table 4

Task Performance

		Accuracy (%)	
Task	**Condition**	**Mean (SD, range)**	
Sound task		Younger cohort	Older cohort
	Onset	62.5 (16.5, 25–96)	70.8 (12.7, 38–92)
	Rhyme	81.2 (13.3, 50–100)	88.0 (9.9, 58–100)
	Unrelated	81.1 (13.3, 50-100)	84.6 (10.9, 46–100)
	Perceptual	90.4 (10.3, 63-100)	95.8 (5.8, 71–100)
Meaning task			
	Low	74.7 (16.3, 33–96)	83.6 (11.9, 46–100)
	High	82.4 (9.9, 63–100)	89.9 (7.2, 67–100)
	Unrelated	76.0 (15.5, 33-96)	83.2 (10.3, 58–100)
	Perceptual	92.8 (6.4, 79-100)	96.7 (4.4, 79–100)

Note. The table displays accuracies (%) for each condition during the sound and the meaning judgment tasks for the younger and older cohorts. SD: standard deviation.

fMRI data acquisition

Participants laid in the scanner with a response button box placed in their right hand. To keep participants focused on the task, visual stimuli were projected onto a screen and viewed via a mirror attached to the head coil. Participants wore MRI-compatible insert earphones (Sensimetrics, Model SI4) to hear the auditory stimuli, and pads in between the earphones and the head coil were used to attenuate scanner noise. Images were acquired using a 3.0 T Skyra Siemens scanner with a 64-channel head coil. The blood oxygen level dependent (BOLD) signal was measured using a susceptibility weighted single-shot echo planar imaging (EPI) method. Functional images were acquired with multiband EPI. The following parameters were used: TE = 30 ms, flip angle = 80, matrix size = 128 × 128, FOV = 256 mm^2, slice thickness = 2 mm without gaps, number of slices = 56, TR = 1,250 ms, multi-band acceleration factor = 4, voxel size = 2 × 2 × 2 mm. A high-resolution T1-weighted MPRAGE scan was acquired prior to functional image acquisition with the following scan parameters: TR = 1900 ms, TE = 2.34 ms, matrix size = 256 × 256, FOV = 256 mm^2, slice thickness = 1 mm, number of slices = 192.

fMRI data analysis

Preprocessing

Statistical Parametric Mapping 12 (SPM12, http://www.fil.ion.ucl.ac.uk/spm) was used to analyze the MRI data. First, all functional images were realigned to their mean functional image across runs. The anatomical image was segmented and warped to a pediatric tissue probability map template to get the transformation field. An anatomical brain mask was created by combining the segmented products (i.e., gray, white, and cerebrospinal fluid), and then applied to its original anatomical image to produce a skull-stripped anatomical image. All functional images, including the mean functional image, were coregistered to the skull-stripped anatomical image. Functional images were then normalized to a pediatric template by applying the transformation field to them and re-sampled with a voxel size of 2 × 2 × 2 mm. The pediatric tissue probability map template was created using CerebroMatic (Wilke et al., 2017), a tool that makes SPM12 compatible pediatric templates with user-defined magnetic field parameters, age, and sex. The unified segmentation parameters estimated from 1919 participants (Wilke et al., 2017, downloaded from https://www.medizin.uni-tuebingen.de/kinder/en/research/neuroimaging/software/) were used. Parameters were defined as a magnetic field strength of 3.0 T, age range from 5.5 to 8.5 years old with 1-month intervals, and sex as two females and two males at each age interval, resulting in a sample of 148 participants, to obtain our age-appropriate pediatric template. After normalization, smoothing was applied to all the functional images with a 6 mm isotropic Gaussian kernel. To reduce movement effects on the brain signal, Art-Repair (Mazaika et al., 2009) was used to identify outlier volumes, defined as those with volume-to-volume head movement exceeding 1.5 mm in any direction, head movements greater than 5 mm in any direction from the mean functional image across runs, or deviations of more than 4% from the mean global signal intensity. Outlier volumes were then repaired using interpolated values of the adjacent non-outlier scans. All participants in both cohorts included in the final analysis had no more than 10% of the volumes and no more than six consecutive volumes repaired within each run.

First level (within-subject) analysis

Statistical analyses performed at the individual and group level were run with code adapted from Wang et al. (2021), which were published online by the authors on GitHub (https://github.com/wangjinvandy/PhonSem_Specialization_7-8). A copy of the exact codes use for this project can be found on https://github.com/comptoab/HLE_PhonSem_Specialization. All four conditions in each task and each run (i.e., Onset, Rhyme, Unrelated, and Perceptual in the sound judgment task, and Low, High, Unrelated, and Perceptual in the meaning judgment task) were entered into the first-level general linear model as regressors of interests, with the addition of six motion parameters estimated during realignment entered as regressors of no interest (repaired volumes were deweighted). Statistical analyses at the 1st level were calculated using an event-related design. Data were high-pass filtered with a cut-off period of 1/128 Hz and with an SPM default mask threshold of 0.5. All experimental trials were included as individual events for analysis and modeled using a canonical hemodynamic response function. To obtain the brain activation map for phonological processing within each participant, Related conditions (i.e., Onset + Rhyme) were compared with the Perceptual condition during the sound judgment task. To obtain the brain activation map for semantic processing within each participant, Related conditions (i.e., High + Low) were compared with the Perceptual condition during the meaning judgment task. To examine phonological specialization within each participant, a contrast of the sound task (Related > Perceptual) > the meaning task (Related > Perceptual) was computed. To examine semantic specialization within each participant, a contrast of the meaning task (Related > Perceptual) > the sound task (Related > Perceptual) was computed. To examine semantic and phonological sensitivity, we calculated the parametric modulation effect within each participant, the two Related conditions within each task (Onset > Rhyme in the sound task, and Low > High in the meaning task) were contrasted.

Second level (group) analysis

In this study, we focused on specific predictions regarding a relation between HLE and phonological and semantic specialization in the frontal and temporal left hemisphere in the younger and older cohorts based on results reported by Weiss et al. (2018) and Wang et al. (2021). Thus, we tested our a-priori hypotheses using a language region of interest (ROI), defined by the overlap between a whole-brain functional activation map and an anatomical mask (consistent with Weiss et al. (2018) and Wang et al. (2021)) and used in subsequent analyses. The functional activation maps – separate for both younger and older cohorts – were created using the union of activation maps obtained from each task using the contrast [(Rhyme + Onset) > Perceptual] for the sound task and the contrast [(High + Low) > Perceptual] for the meaning task, at a threshold of voxel-wise $p < .001$, cluster size > 0. The anatomical mask was made by combining the left IFG, left MTG, and left STG using the WFU PickAtlas toolbox.

All subsequent analyses were performed separately for each group. A series of within-ROI one-sample t-tests were firstly computed to replicate the main effects of functional specialization and sensitivity previously reported by Wang et al., 2021 and Weiss et al., 2018 (for results see Supplementary Material, Figure S2). Task comparison contrast maps from each individual (the sound task > the meaning task, or the meaning task > the sound task) were entered into a one-sample t-test to generate a brain specialization map at the group level for either phonological or semantic processing (see Figure S2A and S2B). Additionally, contrast maps for functional sensitivity from each individual (i.e., Onset > Rhyme, or Low > High) were also entered into a one-sample t-test to generate a brain sensitivity map at the group level for either phonological or semantic processing (see Figure S2C, S2D, and S2E). This analysis was not preregistered as it did not focus on the core questions of this study.

Next, a series of preregistered brain-behavior correlation analyses were performed to examine the relationships between HLE and functional specialization. The task comparison contrast maps from each participant for phonological specialization (sound > meaning judgment) and semantic specialization (meaning > sound judgment) together with HLE scores were entered into voxel-wise regression models. For the younger group, HLE measured as a) amount of time a child reads each day (child independent reading) and b) amount of time a child is read to by an adult each day (family-to-child reading) was included as a covariate of interest. For the older group, HLE measured as a) frequency with which a child reads to themself or others outside of school each week (child independent reading) and b) frequency with which a child is read to by a family member each week (family-to-child reading) was included as a covariate of interest. All voxel-wise regression analyses were additionally controlled for each participant's in-scanner task performance, measured as a mean accuracy score (%) across both runs in either the sound judgment task (Rhyme & Onset) or the meaning judgment task (High & Low), depending on the analysis, as well as age (in months), all of which were included in the models as nuisance covariates. Subsequently, all analyses were repeated with SES score (see section "Participants"), added as an additional covariate of no interest. For detailed information about nuisance covariates values for each cohort see Table 2. To provide strong evidence of a relation, clusters within the language ROI surviving a small volume correction (SVC; Worsley et al., 1996) at a voxel-wise $p < .001$, and a cluster-wise $p < .05$ FWE corrected level were used to determine the results' significance.

After the examination of functional specialization, another series of preregistered secondary brain-behavior analyses were computed to investigate whether HLE is associated with the functional sensitivity to phonological and semantic processing. Contrast maps from each participant for parametric effects in the sound task (Onset > Rhyme) and the meaning task (Low > High) were included in regression models with HLE scores included as covariates of interest. Second, all the above analyses were duplicated at the whole-brain level without using the language ROI. All preregistered secondary analyses were controlled for additional factors in the same manner as preregistered primary analyses: first for age and in-scanner performance and, in the subsequent set of analyses, SES in addition to age and in-scanner performance. To provide strong evidence of a relation, clusters within the language ROI surviving a SVC (Worsley et al., 1996) at a voxel-wise $p < .001$, and a cluster-wise $p < .05$ FWE corrected level were used to determine the results' significance.

In addition to using a strict threshold to seek for strong evidence, we additionally explored preregistered regression results for specialization and sensitivity (within language ROI) at a lenient significance threshold of $p < .05$, uncorrected, k > 20. All clusters at this lenient threshold are included in the supplementary materials, Table S4. To simplify discussion of exploratory results, we focus on clusters greater than k > 40 and consider this to be only weak evidence of the relation. _This practice of transparently reporting fMRI results at both strict and lenient thresholds to avoid missing weak but important evidence is also applied in other studies (e.g., Wang et al., 2020). We preregistered all the analyses for each age group separately to maximize the sample sizes, which did not allow us to directly compare developmental changes within the same individuals. However, given a potential developmental transition from the temporal to the frontal lobes observed in previous cross-sectional studies (e.g., Weiss et al., 2018; Wang et al., 2020), we also proposed hypotheses in our preregistered hypotheses and displayed brain location differences between the younger and the older cohorts in the associations between HLE and functional specialization or sensitivity.

Deviation from preregistration

For the 5-6-year-old age group, the preregistration states "for movement detection method see Weiss et al., 2018." In this study, we adhered to the movement threshold used in Wang et al.

(2021) across age groups, rather than the movement detection method used in Weiss et al. (2018) for the younger age group.

Weiss et al., (2018) defined outlier volumes as “those with head movement exceeding 4 mm in any direction or deviations of more than 1.5% from the mean global signal” whereas Wang et al. (2021) defined outlier volumes as “those with volume-to-volume head movement exceeding 1.5 mm in any direction, head movements greater than 5 mm in any direction from the mean functional image across runs, or deviations of more than 4% from the mean global signal intensity.” In both studies, outlier volumes were then repaired using interpolation based on the nearest non-outlier volumes. Participants included in both studies had no more than 10% of the volumes from each run and no more than six consecutive volumes interpolated. We adhered to the Wang et al. (2021) movement detection method to keep consistency across groups at the more stringent movement threshold, as it checks for movements greater than 5 mm in any direction from the mean functional image.

Additionally, analyses were also performed at a more lenient significance threshold, that was not preregistered, post hoc behavioral analyses were not preregistered, and the examination of main effects were not preregistered, but included in the supplementary material for illustrative purposes. These sections and results are labeled accordingly.

Results

The overviews of analyses for the correlations of reading behavior to activation are presented in Figures 1, 2 and Tables 5, 6 (for analyses without controlling for SES) as well as Figures S3, S4 and Tables S2, S3 (for analyses controlling for SES). Main effects of task and condition were examined for illustrative purposes and are presented in Figure S2 and Table S1. In the tables, anatomical regions were determined with reference to Anatomical Atlas Labeling (AAL) version 1. Coordinates are reported in MNI space.

Preregistered analyses

Correlation with functional specialization (task differences) within ROI (preregistered primary)

In the ROI, there was no strong evidence (voxel-wise $p < .001$, and a cluster-wise $p < .05$ FWE corrected level) indicating a positive correlation between phonological or semantic specialization-related brain activation and HLE revealed by regression analyses when SES was not included as a covariate. Specifically, we did not find strong evidence for the association of the strength of task differences with family-to-child or child independent reading score for either 5- to 6- or 7- to 8-year-old children (see Figures 1 and 2 for an overview, along with Tables 5 and 6). There remained no strong evidence when SES was added as a nuisance covariate (see Figures S3 and S4 in the Supplementary Material for an overview along with Tables S2 and S3)

Correlation with functional specialization (task differences) in the whole brain (preregistered secondary)

In the whole brain, like the ROI results, there was no strong evidence indicating a positive correlation between phonological or semantic specialization-related brain activation and HLE revealed by regression analyses when SES was not included as a covariate. Specifically, we did not find strong evidence for the association of the strength of task differences with family-to-child or child independent reading score for either 5- to 6- or 7- to 8-year-old children (see Figures 1 and 2 for an overview along with Tables 5 and 6). There remained no strong evidence when SES was added as a nuisance covariate (see Figures S3 and S4 in the Supplementary Material for an overview along with Tables S2 and S3)

Correlation with functional sensitivity (condition differences) within ROI (preregistered secondary)

In the ROI, for family-to-child reading, there was no strong evidence for a correlation with phonological sensitivity (Onset > Rhyme) in either the younger or older groups. However, there was strong evidence for a positive correlation of semantic sensitivity (Low>High) in the left MTG in older, but not younger children. The strong evidence remained the same when the analysis was not controlled for SES (see Figure 2 and Table 6) and when SES was added as a nuisance covariate (see Figure S3 and Table S3 in the Supplementary Material). There was no strong evidence of associations between child independent reading and phonological (Onset > Rhyme) or semantic (Low > High) sensitivity in either the younger or older groups.

Correlation with functional sensitivity (condition differences) in the whole brain (preregistered secondary)

In the whole-brain, similar to the ROI results, for family-to-child reading, there was no strong evidence for a correlation with phonological sensitivity (Onset > Rhyme) in either the younger or older groups. However, whole-brain analyses confirmed its association with semantic sensitivity (Low > High) within the left MTG in the older cohort. When the analysis was not restricted to the language ROI, the effect extended to the middle occipital gyrus. The strong evidence remained the same when not controlled for SES (see Figure 2 and Table 6) and with SES added as a nuisance covariate (see Figure S3 and Table S4). There was no strong evidence for the associations between child independent reading and brain sensitivity depicted in Figures 1 and 2, as well as S3 and S4.

Non preregistered analyses

Correlation of functional specialization (task differences) in ROI at reduced threshold (exploratory)

In the ROI, a lenient significance threshold (p < .05, uncorrected, k > 40) was also used in exploratory analyses to examine weak evidence in the data. For family-to-child reading, weak evidence for an association with the strength of phonological specialization was observed in the left STG in both the younger and older groups (see Figure 2 and Table 6) when SES was not controlled for. But when controlled for SES, active voxels remained only in the younger children (see Figure S3 and Table S4). Weak evidence for a positive correlation to semantic specialization was also found, but only in the older children in the left STG, left MTG, and left IFG. The effects remained the same when not controlling for SES (see Figure 2 and Table 6) and when controlling for SES (Figure S3 and Table S4). As for child independent reading, the analyses did not reveal weak evidence of a positive correlation with phonological specialization in either the younger or older group when SES was not controlled (see Figure 1 and Table 5). However, when the analysis was controlled for SES, a cluster in the left STG was found in the older children (see Figure S3 and Table S3). In contrast to the relation to phonological specialization, weak evidence for a positive correlation with semantic specialization was observed in both the younger and older groups: in the left STG in younger children and in the left IFG and left MTG in the older children. The effect remained the same when the analysis was not controlled for SES (see Figure 1 and Table 5) and when SES was added as a nuisance covariate (see Figure S3 and Table S3).

Correlation of functional sensitivity (condition differences) in ROI at reduced threshold (exploratory)

In the ROI, for family-to-child reading, analysis revealed weak evidence of a positive correlation with phonological sensitivity (Onset > Rhyme) in the left STG in younger children, with and without controlling for SES (see Figure 1 and S3). Weak evidence of a positive correlation was found between family-to-child reading score and semantic sensitivity (Low > High) only in older children within the left IFG and MTG, with and without controlling SES (See Figure 2 and S3 along with Table 6 and Table S4). For child independent reading, the analysis also revealed weak evidence of a positive correlation with phonological sensitivity (Onset > Rhyme) in the left STG and left MTG only in younger but not older children, with and without controlling for SES (only MTG when SES is controlled; see Figure 1 and S3). No correlation of child independent reading to semantic sensitivity (Low > High) was observed.

Behavioral analyses (exploratory)

Following the fMRI analyses, behavioral analyses were conducted examining the relation of family-to-child reading to standardized scores of phonological awareness and semantics measured with CTOPP-2 Elision and CELF-5 Word Classes scores, respectively (see Table 7 for an overview). We examined relations with family-to-child reading as there were significant brain-behavior relations with this variable at the most stringent threshold.

Table 7.

Standardized Assessments

		Scaled Scores	
Construct	**Assessment**	**Mean (SD, range)**	
		Younger cohort	Older cohort
Phonology	CTOPP-2 Elision	11.8 (2.3, 9–19)	12.0 (2.5, 7–17)
Semantics	CELF -5 Word Classes	14.0 (3.4, 7–19)	12.9 (3.3, 3–19)

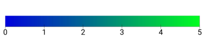
Note. The table displays scaled scores from standardized assessments of phonology (CTOPP-2 Elision) and semantics (CELF-5 Word Classes) for the younger (5-6-year-olds) and older (7-8-year-olds) cohort. SD: standard deviation.

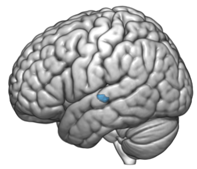
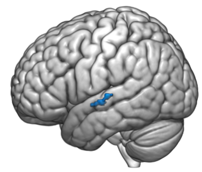
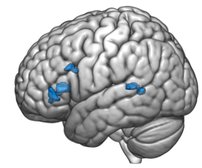
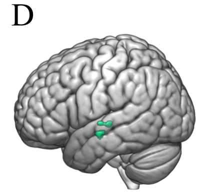
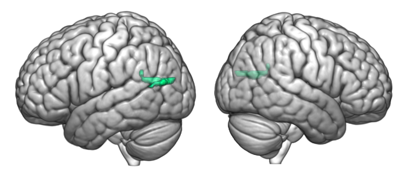
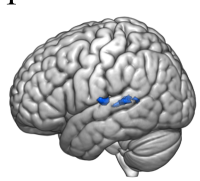
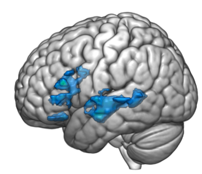
These relations were examined separately for the younger and older age groups using a total of four partial spearman correlations, because family-to-child reading was not normally distributed according to results from a Shapiro-Wilk test for normality. In all analyses, age in months was added as a covariate of no interest. Significance was assessed at $p < .0125$ to account for the four tests conducted. Across analyses, family-to-child reading was not significantly related to standardized phonological awareness score in the younger ($r = .05$, $p = .79$) and older cohorts ($r = -.56$, $p = .06$), nor was it significantly related to standardized semantic score in the younger ($r = .03$, $p = .85$) and older cohorts ($r = -.07$, $p = .56$).

We also checked the correlation of our HLE variables and found that these variables were not significantly correlated for the group of children 5-6 years old ($r = .30$, $p = .09$) or the group of children 7-8 years old ($r = .11$, $p = .32$), supporting our decision to examine these variables separately in analyses. Spearman correlations were completed, given that these values were not normally distributed. Additionally, neither HLE variable was significantly correlated with SES or age for children 5-6 years old or children 7-8 years old.

Figure 1

Family-to-Child Reading

	Sound>Meaning		Meaning>Sound	
	5-6-year-olds	7-8-year-olds	5-6-year-olds	7-8-year-olds
ROI	NS	NS	NS	NS
Whole Brain	NS	NS	NS	NS
ROI, Reduced Threshold	A	B	No Clusters	C

				
	Onset>Rhyme		Low>High	
	5-6-year-olds	7-8-year-olds	5-6-year-olds	7-8-year-olds
ROI	NS	NS	NS	D 
Whole Brain	NS	NS	NS	E 
ROI, Reduced Threshold	F 	No Clusters	No Clusters	G 

Note. Renderings of correlation (not controlling for SES) of family-to-child reading score with functional specialization (task differences: sound > meaning or meaning > sound) and sensitivity (condition differences: Onset > Rhyme or Low > High) for the young (5-6-year-olds) and older (7-8-year-olds) children. Analyses were calculated within the ROI and at the whole brain level for preregistered analyses ($p < .05$ FWE, height threshold $p < .001$), and for a reduced threshold within the ROI for exploratory analyses (extent threshold > 40, height threshold $p < .05$). Clusters are shown in Table 5.

Table 5

Family-to-Child Reading

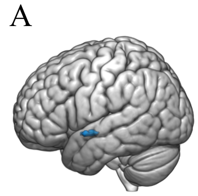
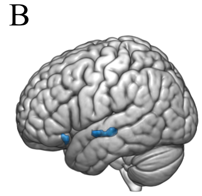
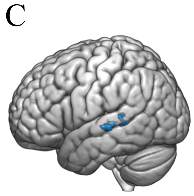
Anatomical Region	BA	X, Y, Z	Voxels	T-value
A) 5-6-year-olds, Sound > Meaning, ROI, Reduced Threshold				
Left superior temporal gyrus	22	-48, -18, 0	46	2.51
B) 7-8-year-olds, Sound > Meaning, ROI, Reduced Threshold				
Left superior temporal gyrus	22	-70, -20, 6	44	2.32
Left middle temporal gyrus	21	-68, -14, 0		2.21
Left superior temporal gyrus	22	-64, -6, -2		2.02
C) 7-8-year-olds, Meaning > Sound, ROI, Reduced Threshold				
Left middle temporal gyrus	21	-62, -52, 8	135	3.03
Left superior temporal gyrus	22	-64, -40, 14		2.53
Left middle temporal gyrus	21	-48, -42, 12		2.12
Left inferior frontal gyrus (triangular part)	45	-40, 32, 2	108	2.36
Left inferior frontal gyrus (triangular part)	45	-48, 30, 8		2.29
Left inferior frontal gyrus (triangular part)	45	-44, 20, 8		2.15
Left inferior frontal gyrus (triangular part)	45	-48, 14, 28	64	2.45
Left inferior frontal gyrus (triangular part)	45	-54, 38, 2	61	2.52
Left inferior frontal gyrus (triangular part)	45	-56, 30, -2		1.90
D) 7-8-year-olds, Low > High, ROI				
Left middle temporal gyrus	21	-60, -12, -8	68	4.01
Left middle temporal gyrus	21	-62, -20, 2	46	4.06
E) 7-8-year-olds, Low > High, Whole Brain				
Left middle occipital gyrus	19	-48, -78, 20	255	5.05
Left middle temporal gyrus	21	-40, -68, 20		4.16
Left middle occipital gyrus	19	-42, -84, 22		3.99
F) 5-6-year-olds, Onset > Rhyme, ROI, Reduced Threshold				
Left superior temporal gyrus	22	-44, -40, 10	129	3.13
Left middle temporal gyrus	21	-52, -30, 6		2.87
Left middle temporal gyrus	21	-64, -36, 10		2.49
Left superior temporal gyrus	22	-68, -14, 14	40	2.32
G) 7-8-year-olds, Low > High, ROI, Reduced Threshold				
Left middle temporal gyrus	21	-62, -20, 2	1493	4.06
Left middle temporal gyrus	21	-60, -12, -8		4.01
Left middle temporal gyrus	21	-62, -48, 2		3.37
Left inferior frontal gyrus (triangular part)	45	-58, 26, 22	822	3.76
Left inferior frontal gyrus (triangular part)	45	-48, 24, 18		3.30
Left inferior frontal gyrus (triangular part)	45	-50, 20, 4		3.02
Left inferior frontal gyrus pars orbitalis	47	-38, 26, -16	156	3.36

Left inferior frontal gyrus pars orbitalis	47	-28, 28, -14	2.81
Left inferior frontal gyrus pars orbitalis	47	-46, 40, -16	2.71

Note. Clusters of correlation (not controlling for SES) of family-to-child reading score with functional specialization (task differences: sound > meaning or meaning > sound) and sensitivity (condition differences: Onset > Rhyme or Low > High) for the young (5-6-year-olds) and older (7-8-year-olds) children. Renderings are shown in Figure 1.

Figure 2

Child Independent Reading

	Sound>Meaning		Meaning>Sound	
	5-6-year-olds	7-8-year-olds	5-6-year-olds	7-8-year-olds
ROI	NS	NS	NS	NS
Whole Brain	NS	NS	NS	NS
ROI, Reduced Threshold	No Clusters	No Clusters	A 	B 
	Onset>Rhyme		Low>High	
	5-6-year-olds	7-8-year-olds	5-6-year-olds	7-8-year-olds
ROI	NS	NS	NS	NS
Whole Brain	NS	NS	NS	NS
ROI, Reduced Threshold	C 	No Clusters	No Clusters	No Clusters

Note. Renderings of correlation (not controlling for SES) of <u>child independent reading</u> score with specialization (task differences: sound > meaning or meaning > sound) and sensitivity (condition differences: Onset > Rhyme or Low > High) for the young (5-6-year-olds) and older (7-8-year-olds) children. Analyses were calculated within the ROI and at the whole brain level for preregistered analyses ($p < .05$ FWE, height threshold $p < .001$), and for a reduced threshold within the ROI for exploratory analyses (extent threshold > 40, height threshold $p < .05$). Clusters are shown in Table 6.

Table 6.

Child Independent Reading

Anatomical Region	BA	X, Y, Z	Voxels	T-value
A) 5-6-year-olds, Meaning > Sound, ROI, Reduced Threshold				
Left superior temporal gyrus	22	-52, -6, -6	64	3.04
Left superior temporal gyrus	22	-60, 2, 06		2.63
Left superior temporal gyrus	22	-52, 6, -8		2.08
B) 7-8-year-olds, Meaning > Sound, ROI, Reduced Threshold				
Left middle temporal gyrus	21	-54, -22, -4	150	2.94
Left middle temporal gyrus	21	-56, -12, -6		2.42
Left superior temporal gyrus	22	-46, -24, -6		2.31
Left inferior frontal gyrus pars orbitalis	47	-38, 24, -14	43	2.39
C) 5-6-year-olds, Onset > Rhyme, ROI, Reduced Threshold				
Left middle temporal gyrus	21	-48, -30, 2	88	3.12
Left middle temporal gyrus	21	-62, -24, 0		2.52
Left superior temporal gyrus	22	-50, -38, 12	64	2.53
Left middle temporal gyrus	21	-50, -44, 2		2.31
Left middle temporal gyrus	21	-58, -42, 4		2.16

Note. Clusters of correlation (not controlling for SES) of <u>child independent reading</u> score with specialization (task differences: sound > meaning or meaning > sound) and sensitivity (condition differences: Onset > Rhyme or Low > High) for the young (5-6-year-olds) and older (7-8-year-olds) children. Renderings are shown in Figure 2.

Discussion

Our study is significant in that it bridges research on brain specialization and sensitivity for phonological and semantic processing in the early elementary school years and literature on the relation of the home literacy environment (HLE) to the neural basis of language. Our study builds upon prior literature that has shown the relation of HLE to phonological awareness (Niklas & Schneider, 2013) and vocabulary knowledge (Frijters et al., 2000; Sénéchal & LeFevre, 2014) as well as to neural regions involved in language processing (Girard et al., 2021; Horowitz-Kraus et al., 2023; Hutton et al., 2021; Powers et al., 2016). However, these previous studies have not investigated whether HLE is related to brain specialization and sensitivity, nor whether these relations change with age. Addressing these gaps, we investigated the relation of HLE to brain specialization and sensitivity for phonological and semantic processing in separate cohorts of children 5-6 years old and 7-8 years old.

Our findings showed that HLE was related to the temporal regions in younger children and temporal as well as frontal regions in older children, in line with prior literature on the developmental changes of language specialization and sensitivity. Additionally, we observed weak evidence of a relation of HLE to phonological specialization and sensitivity in younger children, weak evidence of a relation of HLE to semantic specialization in older children, and strong evidence of a relation of HLE to semantic sensitivity in older children. This change of HLE effect on phonology and then semantics primarily applied to family-to-child but not child independent reading. We did not preregister separate predictions for family-to-child reading and child independent reading, but because prior research suggests that these practices may vary by age

(Silinskas et al., 2020), we examined their relations separately. Below we discussed our findings in more detail. More generally, the relation of HLE to functional specialization and sensitivity for language processing observed in developing children ages 5-to-6 and 7-to-8 supports the role of environmental inputs in neural specialization, in line with the Interactive Specialization theory.

When interpreting these results, it is important to note that these analyses focus on the correlation between HLE and task differences (i.e., our measure of specialization), or more fine-grained distinctions involving task difficulty (i.e., our measure of sensitivity). Thus, some of the non-significant findings could be due to both tasks or conditions activating similar regions, such as those in the inferior frontal cortex, and exhibiting correlations with HLE. For example, it is not necessarily that younger children's HLE is unrelated to their activation of frontal regions during phonological processing tasks. Rather, these children may be engaging inferior frontal regions during both tasks to a similar extent, as shown in Weiss et al. (2018; Figure 2), who included some of the same participants. The current paper is focused on whether HLE is related to brain specialization and sensitivity.

Family-to-child reading

Preregistered analyses in the older cohort revealed strong evidence (voxel-wise $p < .001$, and a cluster-wise $p < .05$ FWE corrected level) of a positive correlation of family-to-child reading to activation in the left pMTG for semantic sensitivity, shown in the region of interest and whole-brain analyses. This was consistent with weak evidence ($p < .05$, uncorrected, $k > 40$) from the exploratory analyses showing family-to-child reading related to semantic specialization in the left pMTG and left vIFG for older children, and semantic sensitivity for the meaning task in the left pMTG and left vIFG for older children. Weak evidence from exploratory analyses also showed a relation of family-to-child reading to phonological specialization in the left pSTG for both age groups, and to phonological sensitivity for the sound task in the left pSTG only for younger children. Overall, the pattern of results suggests a more robust relation of family-to-child reading to semantics in older children, but phonology in younger children. Additionally, there appears to be a stronger relation of family-to-child reading to temporal brain regions in younger children, but frontal as well as temporal regions in older children.

The Memory, Unification, and Control (MUC) model (Hagoort, 2016) suggests that temporal cortex regions house knowledge representations that have been laid down in memory during acquisition, such as phonological word forms and word meanings (Binder & Desai, 2011; Mesgarani et al., 2014), whereas frontal regions support tasks like memory retrieval. We predicted that in younger children both measures of HLE would be related to activation in temporal regions thought to be associated with storing phonological and semantic representations, but in older children we would see relations with temporal as well as frontal regions, the latter of which are thought to be associated with access to posterior representations. In line with this prediction, we found that, for younger children, correlations of family-to-child reading to task and condition differences were primarily located in the left pSTG. For older children, correlations for task and condition differences were located in the left pMTG and left vIFG. Prior literature examining language specialization using auditory sound and meaning judgment tasks that found that 5–6-year-old children showed a double dissociation in the temporal lobe (Weiss et al., 2018), whereas 7–8-year-old children also showed a double dissociation in the frontal lobe (Wang et al., 2021), exhibiting adult-like language specialization (Booth et al., 2006). This is consistent with the neurocognitive model of language development proposed by Skeide and Friederici (2016) arguing that the frontal lobe language structures mature later than the temporal lobe ones. Wang et al. (2021) found stronger specialization in the frontal lobe compared to the temporal lobe in older children, and suggest this may be because younger children may rely on the quality of linguistic representations whereas older children may have developed mature linguistic representations and rely on linguistic access and manipulations to fine-tune their task performance.

For family-to-child reading, we observed weak evidence suggesting more robust relations with phonological processing in younger children, and strong evidence suggesting more robust relations with semantic processing in older children. Shared book reading in young children may provide experience with sounding out words and letter naming, which supports the acquisition of phonological awareness skills. Indeed, a meta-analysis found that shared book reading impacts phonological awareness skills in young children aged 3 to 6 years old (Parpucu & Ezmeci, 2024). However, other longitudinal research demonstrates relations between levels of parent-child book reading and vocabulary in this younger age group (Farrant & Zubrick, 2013). It is possible that shared reading also relates to vocabulary skills in this younger age group, especially depending on the type of shared reading practice that takes place, but perhaps not as strongly as phonological awareness. Young children are still acquiring foundational skills related to phonological awareness that ultimately allow the spellings of words to become bonded to pronunciations as well as meanings and stored in memory (Ehri, 2020). Older children who have mastered foundational skills may be more focused on vocabulary growth. Parent involvement in teaching children about reading appears to be related to the development of early literacy skills, such as phonological awareness in the first grade, whereas children's book exposure may be related to vocabulary skills in the third grade (Sénéchal & LeFevre, 2002).

Some previous literature has examined the relation of HLE to language or reading processing in the brain. For instance, Hutton et al. (2015) used a story listening task in a study of children 3-5 years old. The authors found a relation between higher reading exposure, which included frequency of shared reading, and neural activation in the left temporo-parietal cortex. Some neuroimaging studies have examined relations between HLE and activation in regions implicated in phonological processing or semantic processing. Specifically, Powers et al. (2016) investigated the relation between a composite HLE score and neural activation during a phonological processing task with children who had an average age of around 5.5 years. They found a relation between HLE and activation in areas including the IFG and STG, suggesting an impact on the manipulation of phonological code. Girard et al. (2021) examined a group of children with a mean age of 8.5 years and found that children with a higher composite HLE score exhibited heightened sensitivity to the repetition of print words in part of the IFG. Furthermore, they found a mediating effect of vocabulary between HLE and activation during the word adaptation task. Although the studies are limited, results suggest relations of HLE with phonological processing in younger children and semantic processing in older children. The present study was unique in that it investigated both semantic and phonological tasks in one study in younger and older children.

The developmental reliance on phonological processing in younger children and semantic processing in older children may also be because of differences in the books and the type of shared reading. Future work could examine these differences by collecting data on the types of books with which the child interacts. Some children's books and shared reading practices are geared more towards increasing phonological awareness skills, and others towards vocabulary expansion. Some books emphasize patterns like rhyming and sound learning, whereas others focus more on vocabulary and are narrative-focused. Stadler and McEvoy (2003) found that, in a group of preschoolers, alphabet books elicited a higher rate of phonological awareness behaviors while narrative books resulted in parents using more content behaviors. Similarly, Riordan et al. (2018) suggest that, based on their study on preschoolers, rhyming picture books may elicit code-focused talk, and non-rhyming picture books may elicit meaning-focused talk. Flack et al. (2018) conducted a meta-analysis on the effects of shared storybook reading on word learning. The study found that storybooks read to older children include more target words and fewer occurrences of those words than those read to younger children, thus supporting more advanced vocabulary acquisition. Teacher resources also note that younger children (4-5 years old) often enjoy rhyming books and concept books, such as alphabet books, whereas older children (6-8 years old) may enjoy stories with more complex plot lines (Maddigan et al., 2005). It may be that young children are exposed during shared reading to books that emphasize phonological processing, such as rhyming, but older children are engaged in shared reading activities that focus more on semantic processing, such as learning the meaning of new words.

Child independent reading

Weak evidence from exploratory analyses, at a lenient significance threshold, showed a relation for child independent reading to (1) phonological specialization in the left pSTG for older children, (2) phonological sensitivity in the left pSTG and pMTG for younger children, and (3) semantic specialization in the left pSTG for younger children and in the left vIFG and left pMTG for older children. The pattern of results is inconsistent with our expectations of more robust effects for the rhyming task in pSTG and dIFG and for the meaning task in pMTG and vIFG. However, consistent with the family-to-child reading results, we continue to generally see a relation to temporal brain regions in younger children and frontal as well as temporal regions in older children. One reason there may be less consistent associations with child independent reading is that what a child does during independent reading time can vary greatly. Kelley and Clausen-Grace (2010) identified a continuum of engaged reading profiles from “Fake Readers” to “Bookworms” and indicated the amount and type of support required based on these profiles to foster meaningful independent reading time. Higher-skill readers often need less support to make independent reading time effective than challenged readers. A meta-analysis on the effects of silent independent reading practices in students from kindergarten through 12th grade with no monitoring and no specific feedback found no meaningful beneficial effects of independent reading, but the authors note there are conditions under which independent reading could be effective (Erbeli & Rice, 2022). Future work should further investigate relations between more specific measures of child independent reading time and specialization for phonology and semantics.

Role of socioeconomic status (SES)

Prior literature has indicated that SES relates to reading and the brain (Noble et al., 2006). SES is a more distal variable whereas questions on child reading are a more proximal measure of experience. Some studies have found a mediating effect of HLE on the relation of SES to language (Jiang et al., 2024). Prior literature also suggests that reading to children across levels of SES is beneficial (Ergül et al., 2016) and that dialogic reading interventions can be effective for children regardless of SES (Dowdall et al., 2020).

Literature examining brain-behavior relations with HLE often control for SES (Girard et al., 2021; Hutton et al., 2015; Powers et al., 2016). In line with theoretical models and behavioral research (Jiang et al., 2024), future work on brain-behavior relations, with a larger range of SES, could examine brain data with mediation models to better capture real-world relations. In the present sample, participants had relatively high levels of SES, and SES was not significantly correlated with our measures of HLE, so a mediation model would not have been appropriate. Analyses were completed with and without controlling for SES, situating findings among prior literature while also demonstrating relations without controlling for a variable that is theoretically a distal variable in the model.

Across our analyses, most effects were present whether SES was controlled or not. At a lenient significance threshold, however, we see some differences in correlations with phonological specialization when controlling for SES. Specifically, the two differences were that (1) there was a relation of family-to-child reading and phonological specialization for both age groups, but only younger children when controlling for SES and (2) a relation of child independent reading and phonological specialization for older children only when controlling for SES. Although this pattern is unclear, we see weak evidence in line with prior literature suggesting that SES relates to brain differences in phonological processing (Conant et al., 2017; Younger et al., 2019). For example, an fMRI study on children during a phonology task found that those with low levels of SES exhibited less left lateralization in the STG (Younger et al., 2019).

Limitations and conclusion

A limitation of this study is the relatively small sample size in younger children (N = 33) compared to older children (N = 76), though the total number of participants in this study is larger than other similar studies (Girard et al., 2021; Hutton et al., 2015; Powers et al., 2016). Another limitation is that we used one parent report question to index the amount or frequency of family-to-child reading, so we could not measure the quality of the shared book reading. Furthermore, these questions differed slightly for each age group, given the surveys administered to different age groups in the study. Other factors are also likely to influence the brain specialization for language. For example, Dong et al. (2020) found that parents' involvement and literacy expectations of children had a significantly higher correlation with children's reading comprehension than home literacy resources (e.g., number of books in the home) did. Future work would benefit from more specific measures of HLE that ask more questions about or directly measure reading practices. Given the differences in HLE questions, we did not complete direct statistical comparisons between groups but rather only describe results for each age group separately. Future work would benefit from analyses that are able to make direct statistical comparisons between age groups. Participants in the 7-8-year-old group from the dataset that were excluded from analysis were significantly different from those who were included when it came to child-independent reading, such that those included in analyses read to themselves more often than those excluded from analyses. Future work would benefit from participants with a larger range of HLE scores that are aligned with a community sample. Finally, another limitation is that we used mother education level as a measure of SES because this is what was available in the dataset. Although educational attainment is commonly used as a proxy for SES, additional metrics that capture information such as occupational prestige or income can be helpful in fully characterizing SES (Diemer et al., 2013).

Although behavioral analyses have previously underscored the importance of HLE to phonology and semantics, and prior brain analyses have illustrated the importance of reading to children starting from a young age (Horowitz-Kraus et al., 2023), this study builds on prior work to examine the relation of HLE to brain specialization for phonology and semantics. It would be interesting to examine dialogic reading practices that are geared toward phonology for younger children and semantics for older children. Namely, should parents be focused on shared reading practices that emphasize phonology in younger children and semantics in older children in order to capitalize on the relations with specialization and sensitivity that seem present at that time?

Despite the limitations, this study underscores the importance of shared reading and specifically suggests a relation of family-to-child reading to functional specialization and sensitivity for processing the sound structure of language at 5 years old and processing meaning at 7 years old, consistent with the literature suggesting the early importance of phonology and later semantics in developing readers. Moreover, across measures of HLE, we generally see a relation to temporal brain regions in younger children and frontal as well as temporal regions in older children, consistent with neuro-cognitive models of language, pointing to a delayed maturation of the frontal cortex. Generally, results stay consistent when controlling for SES and not controlling for SES, suggesting the importance of reading in the home for brain development regardless of SES. Together, this study represents an important and novel contribution to the interactive specialization account of brain development, as it is the first to examine developmental differences in the relation of HLE, an environmental factor, to the brain specialization for language processing.

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Data Availability Statement

The dataset is publicly available on OpenNeuro.org (Wang et al., 2022; https://openneuro.org/datasets/ds003604). A copy of the exact codes use for this project can be found on GitHub (https://github.com/comptoab/HLE_PhonSem_Specialization). The research questions, hypotheses, and analytical plan were preregistered through the Open Science Framework prior to beginning the data analyses (see https://osf.io/d9cxm and https://osf.io/xrgtu).

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Supplementary Material

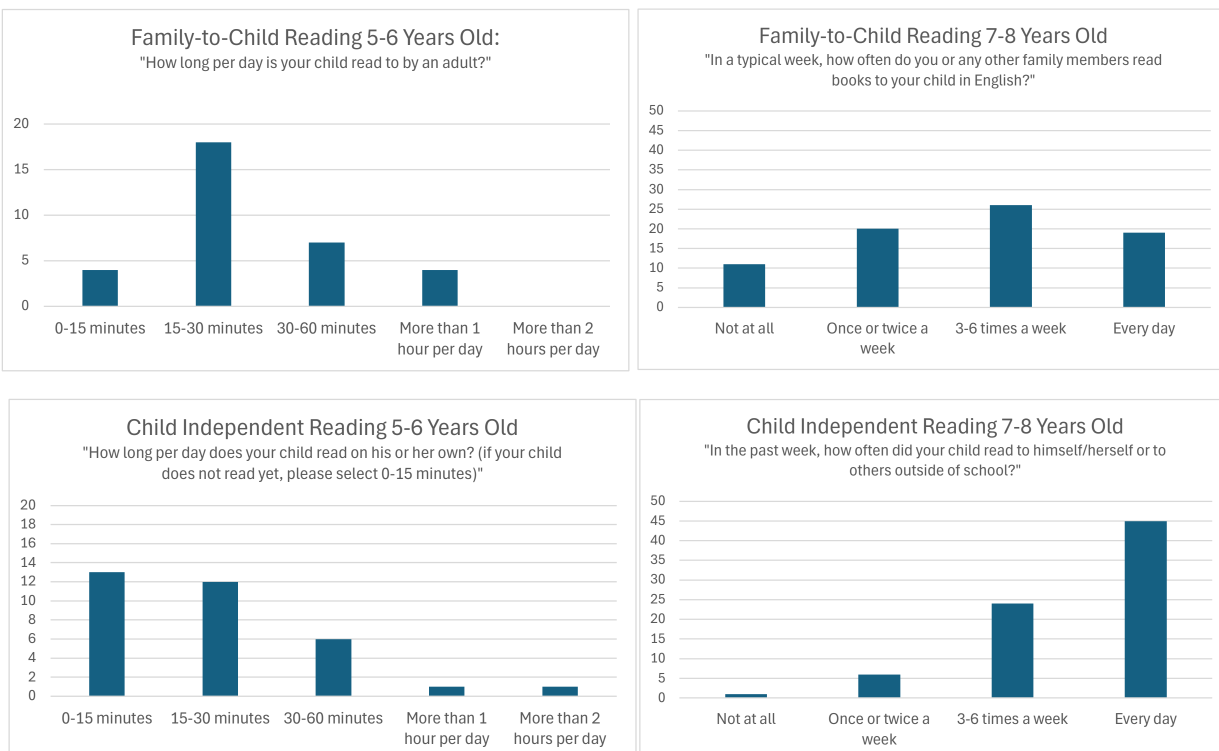
The overviews of analyses for the correlations of reading behavior to activation are presented in Figures 1, 2 and Tables 5, 6 (for analyses without controlling for SES) as well as Figures S3, S4 and Tables S2, S3 (for analyses controlling for SES). Main effects of task and condition were examined for illustrative purposes and are presented in Figure S2 and Table S2. Finally, all clusters at a lenient threshold are described in Table S4.

Supplementary Materials

Distributions of responses for the home literacy environment questions are displayed in Figure S1. The overviews of analyses for the correlations of reading behavior to activation are presented in Figures 1, 2 and Tables 5, 6 (for analyses without controlling for SES) as well as Figures S3, S4 and Tables S2, S3 (for analyses controlling for SES). Main effects of task and condition were examined for illustrative purposes and are presented in Figure S2 and Table S1. Finally, all clusters at a lenient threshold are described in Table S4.

Figure S1

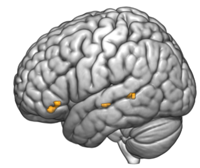
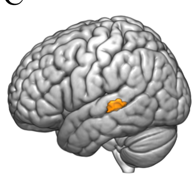
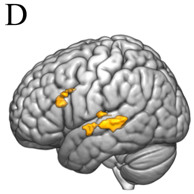
Home Literacy Environment Distributions



Note. Family-to-Child Reading and Child Independent Reading responses for each group are displayed.

Figure S2

Main Effects

	Sound>Meaning		Meaning>Sound	
	5-6-year-olds	7-8-year-olds	5-6-year-olds	7-8-year-olds
ROI	NS	A 	NS	B 
	Onset>Rhyme		Weak>Strong	
	5-6-year-olds	7-8-year-olds	5-6-year-olds	7-8-year-olds
ROI	C 	D 	NS	E 

Note. Renderings of specialization (task differences: sound > meaning or meaning > sound) and sensitivity (condition differences: onset > rhyme or weak > strong) for the young (5-6-year-olds) and older (7-8-year-olds) children. Clusters are shown in Table S1. The same statistical threshold was used as in Wang et al., 2021 for older children ($p < 0.05$ 3dClustSim corrected, height threshold $p < .001$) and Weiss et al., 2018 for younger children ($p < 0.05$ FWE, height threshold $p < .005$), because these papers were on the same data but did not examine the home literacy environment.

Table S1

Main Effects

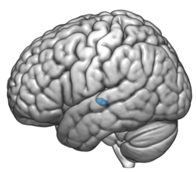
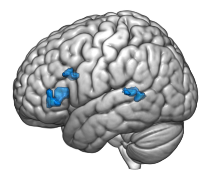
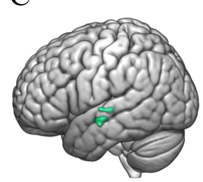
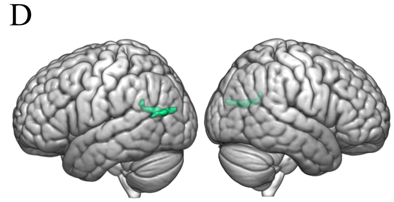
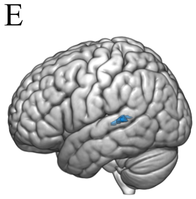
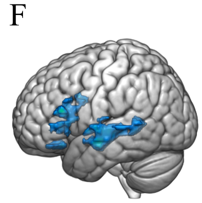
Anatomical Region	BA	X, Y, Z	Voxels	T-value

A) 7-8-year-olds, Sound > Meaning, ROI				
Left Insula	13	-36, 28, 6	23	3.96
B) 7-8-year-olds, Meaning > Sound, ROI				
Left inferior frontal gyrus pars orbitalis	47	-52, 30, -4	55	3.94
Left inferior frontal gyrus pars orbitalis	47	-44, 36, -12		3.64
Left middle temporal gyrus	21	-48, -42, 2	40	3.78
Left middle temporal gyrus	21	-62, -46, 4		3.60
Left middle temporal gyrus	21	-50, -20, -6	19	3.68
C) 5-6-year-olds, Onset > Rhyme, ROI				
Left middle temporal gyrus	22	-66, -40, 4	133	4.19
Left middle temporal gyrus	21	-66, -30, 4		3.74
Left middle temporal gyrus	21	-70, -36, 10		3.49
D) 7-8-year-olds, Onset > Rhyme, ROI				
Left middle temporal gyrus	21	-68, -34, 4	461	5.78
Left middle temporal gyrus	21	-70, -20, 2		5.36
Left superior temporal gyrus	22	-64, -6, 0		4.99
Left inferior frontal gyrus (triangular part)	45	-52, 18, 32	205	4.81
Left inferior frontal gyrus (triangular part)	45	-44, 24, 22		4.78
Left inferior frontal gyrus (triangular part)	45	-54, 22, 22		4.45
Left superior temporal gyrus	22	-62, -16, 12	54	4.17
Left superior temporal gyrus	22	-66, -26, 12		3.32
E) 7-8-year-olds, Weak > Strong, ROI				
Left inferior frontal gyrus (triangular part)	45	-42, 32, 14	57	4.58

Note. Clusters of main effects. Renderings are shown in Figure S2.

Figure S3

Family-to-Child Reading (controlled for SES)

	Sound>Meaning		Meaning>Sound	
	5-6-year-olds	7-8-year-olds	5-6-year-olds	7-8-year-olds
ROI	NS	NS	NS	NS
Whole Brain	NS	NS	NS	NS
ROI, Reduced Threshold	A 	No Clusters	No Clusters	B 
	Onset>Rhyme		Weak>Strong	
	5-6-year-olds	7-8-year-olds	5-6-year-olds	7-8-year-olds
ROI	NS	NS	NS	C 
Whole Brain	NS	NS	NS	D 
ROI, Reduced Threshold	E 	No Clusters	No Clusters	F 

Note. Renderings of correlation (controlling for SES) of family-to-child reading score with specialization (task differences: sound > meaning or meaning > sound) and sensitivity (condition differences: onset > rhyme or weak > strong) for the young (5-6-year-olds) and older (7-8-year-olds) children. Analyses were calculated within the ROI for planned analyses and at the whole brain level for exploratory analyses ($p < 0.05$ FWE, height threshold $p < .001$), and for a reduced threshold within the ROI for exploratory analyses (extent threshold > 40, height threshold $p < .05$). Clusters are shown in Table S2.

Table S2.

Family-to-Child Reading (controlled for SES)

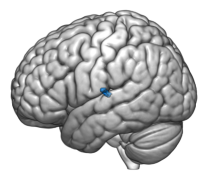
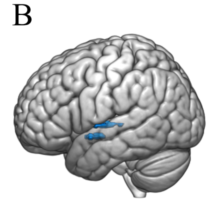
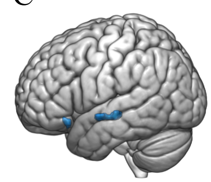
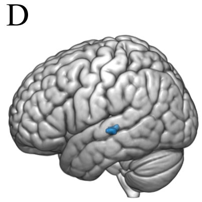
Anatomical Region	BA	X, Y, Z	Voxels	T-value
A) 5-6-year-olds, Sound > Meaning, ROI, Reduced Threshold				
Left middle temporal gyrus	21	-50, -22, 0	42	2.53
B) 7-8-year-olds, Meaning > Sound, ROI, Reduced Threshold				
Left inferior frontal gyrus (triangular part)	45	-46, 26, 12	297	2.72
Left inferior frontal gyrus (triangular part)	45	-54, 38, 2		2.69
Left inferior frontal gyrus (triangular part)	45	-40, 32, 2		2.60
Left middle temporal gyrus	21	-62, -52, 8	196	3.76
Left superior temporal gyrus	22	-66, -44, 14		2.86
Left superior temporal gyrus	22	-50, -42, 14		2.40
Left inferior frontal gyrus (triangular part)	45	-48, 14, 28	140	2.78
Left inferior frontal gyrus (triangular part)	45	-36, 16, 24		2.37
Left inferior frontal gyrus (triangular part)	45	-46, 22, 28		2.36
C) 7-8-year-olds, Weak > Strong, ROI				
Left middle temporal gyrus	21	-58, -12, -8	107	4.29
Left middle temporal gyrus	21	-62, -20, 2	52	4.15
D) 7-8-year-olds, Weak > Strong, Whole Brain				
Left middle occipital gyrus	19	-46, -78, 20	261	5.00
Left angular gyrus	39	-42, -52, 26		4.12
Left middle temporal gyrus	21	-56, -66, 18		3.54

E) 5-6-year-olds, Onset > Rhyme, ROI, Reduced Threshold				
Left superior temporal gyrus	22	-44, -40, 10	47	3.07
Left middle temporal gyrus	21	-52, -30, 6		2.72
Left superior temporal gyrus	22	-68, -40, 12	46	2.36
F) 7-8-year-olds, Weak > Strong, ROI, Reduced Threshold				
Left middle temporal gyrus	21	-58, -12, -8	1484	4.29
Left middle temporal gyrus	21	-62, -20, 2		4.15
Left superior temporal gyrus	22	-58, 0, 2		3.25
Left inferior frontal gyrus (triangular part)	45	-58, 26, 22	844	3.66
Left inferior frontal gyrus (triangular part)	45	-48, 24, 18		3.35
Left inferior frontal gyrus (triangular part)	45	-50, 20, 4		3.19
Left inferior frontal gyrus pars orbitalis	47	-38, 26, -14	164	3.57
Left inferior frontal gyrus pars orbitalis	47	-36, 34, -16		2.87
Left inferior frontal gyrus pars orbitalis	47	-28, 28, -14		2.79

Note. Clusters of correlation (controlling for SES) of family-to-child reading score with task differences (sound > meaning or meaning > sound) and condition differences (onset > rhyme or weak > strong) for the young (5-6-year-olds) and older (7-8-year-olds) children. Renderings are shown in Figure S3.

Figure S4

Child Independent Reading (controlled for SES)

Child Independent Reading (controlled for SES)				
	Sound>Meaning		Meaning>Sound	
	5-6-year-olds	7-8-year-olds	5-6-year-olds	7-8-year-olds
ROI	NS	NS	NS	NS
Whole Brain	NS	NS	NS	NS
Reduced Threshold (within ROI)	No Clusters	A 	B 	C 
	Onset>Rhyme		Weak>Strong	
	5-6-year-olds	7-8-year-olds	5-6-year-olds	7-8-year-olds
Within ROI	NS	NS	NS	NS
Whole Brain	NS	NS	NS	NS
ROI, Reduced Threshold	D 	No Clusters	No Clusters	No Clusters

Note. Renderings of correlation (controlling for SES) of child independent reading score with specialization (task differences: sound > meaning or meaning > sound) and sensitivity (condition differences: onset > rhyme or weak > strong) for the young (5-6-year-olds) and older (7-8-year-olds) children. Analyses were calculated within the ROI for planned analyses and at the whole brain level for exploratory analyses ($p < 0.05$ FWE, height threshold $p < .001$), and for a reduced threshold within the ROI for exploratory analyses (extent threshold > 40, height threshold p < .05). Clusters are shown in Table S3.

Table S3.

Child Independent Reading (controlled for SES)

Anatomical Region	BA	X, Y, Z	Voxels	T-value
A) 7-8-year-olds, Sound > Meaning, ROI, Reduced Threshold				
Left superior temporal gyrus	22	-58, -16, 14	41	2.83
Left superior temporal gyrus	22	-68, -20, 10		1.86
B) 5-6-year-olds, Meaning > Sound, ROI, Reduced Threshold				
Left superior temporal gyrus	22	-58, -16, 6	68	2.73
Left superior temporal gyrus	22	-66, -4, 6		1.91
Left middle temporal gyrus	21	-56, -28, 4		1.90
Left superior temporal gyrus	22	-52, -6, -6	66	2.86
Left superior temporal gyrus	22	-60, 2, -6		2.45
Left superior temporal gyrus	22	-52, 6, -8		2.37
C) 7-8-year-olds, Meaning > Sound, ROI, Reduced Threshold				
Left middle temporal gyrus	21	-54, -22, -4	142	2.89
Left middle temporal gyrus	21	-56, -12, -6		2.37
Left superior temporal gyrus	22	-46, -24, -6		2.26
Left inferior frontal gyrus pars orbitalis	47	-38, 24, -14	42	2.38
D) 5-6-year-olds, Onset > Rhyme, ROI, Reduced Threshold				
Left middle temporal gyrus	21	-46, -28, 0	72	2.94
Left middle temporal gyrus	21	-62, -24, 0		2.51

Note. Clusters of correlation (controlling for SES) of child independent reading score with task differences (sound > meaning or meaning > sound) and condition differences (onset > rhyme or weak > strong) for the young (5-6-year-olds) and older (7-8-year-olds) children. Renderings are shown in Figure S4.

Table S4.

All Clusters (p <0.05 and k>20) in ROIs

Family-to-Child Reading (not controlled for SES)

Anatomical Region	BA	X, Y, Z	Voxels	T-value
A) 5-6-year-olds, Sound > Meaning				
Left superior temporal gyrus	22	-48, -18, 0	46	2.51
B) 7-8-year-olds, Sound > Meaning, ROI, Reduced Threshold				
Left superior temporal gyrus	22	-70, -20, 6	44	2.32
Left middle temporal gyrus	21	-68, -14, 0		2.21
Left superior temporal gyrus	22	-64, -6, -2		2.02
C) 5-6-year-olds, Meaning > Sound				
none				
D) 7-8-year-olds, Meaning > Sound				
Left middle temporal gyrus	21	-62, -52, 8	135	3.03
Left superior temporal gyrus	22	-64, -40, 14		2.53
Left middle temporal gyrus	21	-48, -42, 12		2.12
Left inferior frontal gyrus (triangular part)	45	-40, 32, 2	108	2.36
Left inferior frontal gyrus (triangular part)	45	-48, 30, 8		2.29
Left inferior frontal gyrus (triangular part)	45	-44, 20, 8		2.15
Left inferior frontal gyrus (triangular part)	45	-48, 14, 28	64	2.45
Left inferior frontal gyrus (triangular part)	45	-54, 38, 2	61	2.52
Left inferior frontal gyrus (triangular part)	45	-56, 30, -2		1.90
Left superior temporal gyrus	22	-46, -18, 6	32	3.18
Left superior temporal gyrus	22	-54, -4, -6	23	2.55
E) 5-6-year-olds, Onset > Rhyme				
Left superior temporal gyrus	22	-44, -40, 10	129	3.13
Left middle temporal gyrus	21	-52, -30, 6		2.87
Left middle temporal gyrus	21	-64, -36, 10		2.49
Left superior temporal gyrus	22	-68, -14, 14	40	2.32
Left superior temporal gyrus	22	-54, -10, -2	26	2.34
F) 7-8-year-olds, Onset > Rhyme				
none				
G) 5-6-year-olds, Low > High				
none				

H) 7-8-year-olds, Low > High				
Left middle temporal gyrus	21	-62, -20, 2	1493	4.06
Left middle temporal gyrus	21	-60, -12, -8		4.01
Left middle temporal gyrus	21	-62, -48, 2		3.37
Left inferior frontal gyrus (triangular part)	45	-58, 26, 22	822	3.76
Left inferior frontal gyrus (triangular part)	45	-48, 24, 18		3.30
Left inferior frontal gyrus (triangular part)	45	-50, 20, 4		3.02
Left inferior frontal gyrus pars orbitalis	47	-38, 26, -16	156	3.36
Left inferior frontal gyrus pars orbitalis	47	-28, 28, -14		2.81
Left inferior frontal gyrus pars orbitalis	47	-46, 40, -16		2.71

Child Independent Reading (not controlled for SES)

Anatomical Region	**BA**	**X, Y, Z**	**Voxels**	**T-value**
A) 5-6-year-olds, Sound > Meaning				
none				
B) 7-8-year-olds, Sound > Meaning				
Left superior temporal gyrus	22	-58, -16, 14	29	2.81
Left superior temporal gyrus	22	-68, -20, 10		1.76
C) 5-6-year-olds, Meaning > Sound				
Left superior temporal gyrus	22	-52, -6, -6	64	3.04
Left superior temporal gyrus	22	-60, 2, 06		2.63
Left superior temporal gyrus	22	-52, 6, -8		2.08
Left middle temporal gyrus	21	-62, -44, 8	27	2.34
Left inferior frontal gyrus (triangular part)	45	-52, 32, 10	24	2.93
Left superior temporal gyrus	22	-66, -4, 6	21	2.09
D) 7-8-year-olds, Meaning > Sound				
Left middle temporal gyrus	21	-54, -22, -4	150	2.94
Left middle temporal gyrus	21	-56, -12, -6		2.42
Left superior temporal gyrus	22	-46, -24, -6		2.31
Left inferior frontal gyrus pars orbitalis	47	-38, 24, -14	43	2.39
Left inferior frontal gyrus (triangular part)	45	-50, 20, 4	33	2.88
E) 5-6-year-olds, Onset > Rhyme				
Left middle temporal gyrus	21	-48, -30, 2	88	3.12
Left middle temporal gyrus	21	-62, -24, 0		2.52
Left superior temporal gyrus	22	-50, -38, 12	64	2.53
Left middle temporal gyrus	21	-50, -44, 2		2.31
Left middle temporal gyrus	21	-58, -42, 4		2.16

F) 7-8-year-olds, Onset > Rhyme				
Left inferior frontal gyrus pars orbitalis	47	-28, 24, -14	26	2.56
G) 5-6-year-olds, Low > High				
none				
H) 7-8-year-olds, Low > High				
none				

Family-to-Child Reading (controlled for SES)

Anatomical Region	BA	X, Y, Z	Voxels	T-value
A) 5-6-year-olds, Sound > Meaning				
Left middle temporal gyrus	21	-50, -22, 0	42	2.53
B) 7-8-year-olds, Sound > Meaning				
Left superior temporal gyrus	22	-70, -20, 6	30	2.26
Left middle temporal gyrus	21	-68, -14, 0		2.04
C) 5-6-year-olds, Meaning > Sound				
none				
D) 7-8-year-olds, Meaning > Sound				
Left inferior frontal gyrus (triangular part)	45	-46, 26, 12	297	2.72
Left inferior frontal gyrus (triangular part)	45	-54, 38, 2		2.69
Left inferior frontal gyrus (triangular part)	45	-40, 32, 2		2.60
Left middle temporal gyrus	21	-62, -52, 8	196	3.76
Left superior temporal gyrus	22	-66, -44, 14		2.86
Left superior temporal gyrus	22	-50, -42, 14		2.40
Left inferior frontal gyrus (triangular part)	45	-48, 14, 28	140	2.78
Left inferior frontal gyrus (triangular part)	45	-36, 16, 24		2.37
Left inferior frontal gyrus (triangular part)	45	-46, 22, 28		2.36
Left superior temporal gyrus	22	-46, -18, 6	39	3.64
Left superior temporal gyrus	22	-58, -26, 8	30	2.32
Left superior temporal gyrus	22	-50, -28, 6		1.80
Left superior temporal gyrus	22	-54, -4, -6	29	2.50
Left superior temporal gyrus	22	-54, 4, -4		1.86
E) 5-6-year-olds, Onset > Rhyme				
Left superior temporal gyrus	22	-44, -40, 10	47	3.07
Left middle temporal gyrus	21	-52, -30, 6		2.72
Left superior temporal gyrus	22	-68, -40, 12	46	2.36
Left superior temporal gyrus	22	-68, -14, 14	26	2.17

F) 7-8-year-olds, Onset > Rhyme				
none				
G) 5-6-year-olds, Low > High				
none				
H) 7-8-year-olds, Low > High				
Left middle temporal gyrus	21	-58, -12, -8	1484	4.29
Left middle temporal gyrus	21	-62, -20, 2		4.15
Left superior temporal gyrus	22	-58, 0, 2		3.25
Left inferior frontal gyrus (triangular part)	45	-58, 26, 22	844	3.66
Left inferior frontal gyrus (triangular part)	45	-48, 24, 18		3.35
Left inferior frontal gyrus (triangular part)	45	-50, 20, 4		3.19
Left inferior frontal gyrus pars orbitalis	47	-38, 26, -14	164	3.57
Left inferior frontal gyrus pars orbitalis	47	-36, 34, -16		2.87
Left inferior frontal gyrus pars orbitalis	47	-28, 28, -14		2.79

Child Independent Reading (controlled for SES)

Anatomical Region	**BA**	**X, Y, Z**	**Voxels**	**T-value**
A) 5-6-year-olds, Sound > Meaning				
none				
B) 7-8-year-olds, Sound > Meaning				
Left superior temporal gyrus	22	-58, -16, 14	41	2.83
Left superior temporal gyrus	22	-68, -20, 10		1.86
C) 5-6-year-olds, Meaning > Sound				
Left superior temporal gyrus	22	-58, -16, 6	68	2.73
Left superior temporal gyrus	22	-66, -4, 6		1.91
Left middle temporal gyrus	21	-56, -28, 4		1.90
Left superior temporal gyrus	22	-52, -6, -6	66	2.86
Left superior temporal gyrus	22	-60, 2, -6		2.45
Left superior temporal gyrus	22	-52, 6, -8		2.37
Left middle temporal gyrus	21	-62, -44, 8	36	2.23
Left inferior frontal gyrus (triangular part)	45	-52, 32, 10	29	3.94
D) 7-8-year-olds, Meaning > Sound				
Left middle temporal gyrus	21	-54, -22, -4	142	2.89
Left middle temporal gyrus	21	-56, -12, -6		2.37
Left superior temporal gyrus	22	-46, -24, -6		2.26
Left inferior frontal gyrus pars orbitalis	47	-38, 24, -14	42	2.38
Left inferior frontal gyrus (triangular part)	45	-50, 20, 4	28	2.84
E) 5-6-year-olds, Onset > Rhyme				

Left middle temporal gyrus	21	-46, -28, 0	72	2.94
Left middle temporal gyrus	21	-62, -24, 0		2.51
Left superior temporal gyrus	22	-50, -38, 12	24	2.31
F) 7-8-year-olds, Onset > Rhyme				
Left inferior frontal gyrus pars orbitalis	47	-28, 24, -14	25	2.48
G) 5-6-year-olds, Low > High				
none				
H) 7-8-year-olds, Low > High				
Left middle temporal gyrus	21	-64, -12, -14	28	2.37
Left middle temporal gyrus	21	-54, -16, -14		2.24
Left superior temporal gyrus	22	-58, -4, 2	18	2.10
Left inferior frontal gyrus pars orbitalis	47	-48, 34, -14	13	2.51
Left superior temporal gyrus	22	-58, -32, 12	11	2.29

Note. Clusters of correlation (not controlling for SES) at $p < 0.05$ *and* $k > 20$ of family-to-child reading and child independent reading score with specialization (task differences: sound > meaning or meaning > sound) and sensitivity (condition differences: Onset > Rhyme or Low > High) for the young (5-6-year-olds) and older (7-8-year-olds) children.