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Author Note

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Abstract

Reading skill is foundational to academic and occupational success and therefore understanding the factors that support successful reading development is critical. The current study investigated whether neural specialization for phonological and semantic processing at 5-to-6 years old was predictive of growth in reading skills from 5-to-8 years old. Results from this pre-registered study provide important preliminary evidence in favor the role of early phonological neural specialization in the development of word reading skills.

Keywords: Longitudinal fMRI; Bayesian Methods; Word Reading Development

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Contemporary developmental models argue that children initially rely on a distributed network of brain regions to perform a cognitive skill. However, over time and practice that network narrows, as specific regions begin to specialize. Ultimately, this process of neural specialization is hypothesized to facilitate skill development (e.g., Interactive Specialization Theory; Johnson, 2011). Recent work has established that 5-to-6-year-old children already show neural specialization for oral language skills (e.g., Weiss et al., 2018). While behavioral research has demonstrated that oral language skills support later reading development, limited existing work has explored the neural basis of this relation. The aim of the current study was to address this gap by examining whether early neural specialization for phonological and semantic processing, subcomponents of oral language, predicts growth in word reading skills. Four specific hypotheses were tested: (1) individual differences in phonological and semantic processing will predict variability in reading growth, (2) phonological processing will be a stronger predictor of reading growth than semantic processing, (3) measures of neural specialization will be a stronger predictor of reading growth than behavioral measures, and (4) any observed relation between neural specialization and reading growth will be driven by both an increase in region-appropriate processing (i.e., phonological processing in superior temporal; semantic processing in middle temporal) and a decrease in region-inappropriate processing (i.e., semantic processing in superior temporal; phonological processing in middle temporal).

Method

The hypotheses and analytic approach for this study were pre-registered (see https://osf.io/ek8rc/). An Institutional Review Board approved all study procedures. Before participation, assent and consent were obtained from all participants and their guardians.

Participants

The final sample included 29 children who met the pre-registered inclusionary criteria. At Time 1 (T1), participants (19 female) in the final sample ranged between 4.74 and 6.28 years old (M = 5.75). At Time 2 (T2), participants in the final sample ranged between 7.09 and 8.25 years old (M = 7.43).

Materials

Reading skill was measured behaviorally with the "Letter-Word Identification" subtest at T1 and T2. Participants additionally completed both behavioral- and fMRI-based semantic and phonological tasks at T1. Behaviorally, the "Elision" subtest of the Comprehensive Test of Phonological Processing – 2nd Edition (Wagner et al., 1999) and the "Word Classes" subtest of the Clinical Evaluation of Language Fundamentals – 5th Edition (Wiig et al., 2003) were used to measure individual differences in phonological and semantic processing, respectively. To index phonological and semantic neural specialization, participants completed a Sound Judgment task and a Meaning Judgment task in the MRI scanner. In the Sound Judgment task, participants were auditorily presented with two words and asked to respond with a 'yes' or 'no' button press in response to the question, "Do the two words have any of the same sounds?" There were three experimental conditions in which the words shared the same final vowel and phoneme/cluster (Rhyme), the same initial phoneme (Onset), or no phonemes (Unrelated). In the Meaning Judgment task, participants were auditorily presented with two words and asked to respond with a 'yes' or 'no' button press in response to the question, "Do the two words go together?" There were three experimental conditions in which the words shared a strong semantic association (Strong), a weak semantic association (Weak), or no semantic association (Unrelated). Both tasks also included a control condition in which a pair of frequency modulated noise sounds were presented to which participants were asked to respond with a 'yes' button press. Phonological neural specialization within posterior superior temporal gyrus was indexed by the average beta value within the top 100 activated voxels for the contrast

[(Onset & Rhyme) – Control] > [(Weak & Strong) – Control]. Semantic neural specialization within posterior middle temporal gyrus was indexed by the average beta value within the top 100 activated voxels for the contrast [(Weak & Strong) – Control] > [(Onset & Rhyme) – Control].

Procedure

To evaluate the relation between phonological and semantic skills and reading growth, four regression models were estimated in which growth in reading skill (T2 – T1) was predicted from: (1) the intercept (Null model), (2) performance on the semantic and phonological behavioral tasks (Behavior model), (3) measures of semantic and phonological neural specialization (Brain model), or (4) neural specialization and behavioral performance (Brain-and-Behavior model). Bayes factors (BFs) were used to compare the strength of evidence for each experimental model relative to the Null model. BFs of 10 to 15 were taken as "strong" evidence, 15 to 20 were taken as "very strong" evidence, and greater than 20 were taken as "decisive" evidence that the observed data are more probable under the experimental model over the null model (Jeffreys, 1961). Across the experimental models, the best fitting model was determined by evaluating the Bayesian Information Criterion (BIC) values associated with each model, with the best fitting model exhibiting the smallest BIC value.

Results

Participants showed a significant increase in reading performance from T1 to T2 [BF > 20.00; $t(28) = 14.30$, $p < .001$]. However, contrary to the predictions motivating the current study, the results from the preregistered analyses revealed little to no evidence that measures of semantic and phonological processing were predictive of these reading gains. In fact, it was found that the observed data was ~2.5 times more likely under the Null model for all three experimental models examined [Brain model: BF = 0.47; $F(2, 26) = 1.50$, $p = .242$, $R^2 = .10$; Behavior model: BF = 0.43; $F(2, 26) = 1.36$, $p = .276$, $R^2 = .09$; Brain-and-Behavior model: BF = 0.34; $F(4, 24) = 1.46$, $p = .247$, $R^2 = .20$].

Following the preregistered analyses, exploratory analyses were conducted with three modifications to the analytic approach: (1) the criteria for behavioral performance was relaxed to allow for the inclusion of more participants, (2) the operationalization of reading growth was adjusted to better reflect reading growth relative to initial skill level [(T2-T1)/T1], and (3) only phonologically-based measures were included as predictors, consistent with prior research demonstrating that phonological skills are more predictive of word-level reading than semantic skills (e.g., Muter et al., 2004; Schatschneider et al., 2004).

Parallel hypotheses were created for the exploratory analyses, specifically, it was hypothesized that: (1) individual differences in phonological processing will predict variability in reading growth, (2) measures of neural specialization will be a stronger predictor of reading growth than behavioral measures, and (3) any observed relation between neural specialization and reading growth will be driven by both an increase in region-appropriate processing (i.e., phonological processing in superior temporal) and a decrease in region-inappropriate processing (i.e., semantic processing in superior temporal)

In line with the preregistered analyses, four linear regression models were estimated to evaluate the exploratory hypotheses. Weak evidence was found in favor of a model in which reading growth was predicted by phonological neural specialization [BF = 1.90; $F(1, 39) = 4.72$, $p = .036$, $R^2 = .11$; see Figure 1]. Decisive evidence was found in favor of a model in which reading growth was predicted from Elision performance [BF = 25.65; $F(1, 39) = 12.07$, $p = .001$, $R^2 = .24$; see Figure 2]. However, the strongest evidence was found in favor of a model in which reading growth was predicted from both phonological neural specialization and performance on the behavioral task [BF = 89.76; $F(2, 38) = 9.90$, $p < .001$, $R^2 = .34$; $\beta_{PhonSpecial} = .33$, $p = .018$; $\beta_{Elision} = -.48$, $p < .001$]. An evaluation of the BIC values associated with each model showed that this Brain-and-Behavior model was the best fitting model ($BIC_{Brain} = 52.30$; $BIC_{Behavior} = 45.93$; $BIC_{Brain\text{-}and\text{-}Behavior} = 43.50$). Given that there was moderate evidence for the predictive utility of phonological specialization, a follow-up analysis was conducted to better understand the observed relation between neural specialization and reading growth. A direct comparison between activity

associated with the phonological and semantic tasks in posterior superior temporal gyrus revealed moderate evidence in favor of the null model (in which there is no difference between the tasks), BF = 0.17; $t(40) = -0.101$, $p = .920$, suggesting that both tasks recruited this region to a similar degree.

Figure 1

Relation between Specialization in Posterior Superior Temporal Gyrus (pSTG) and Reading Growth.

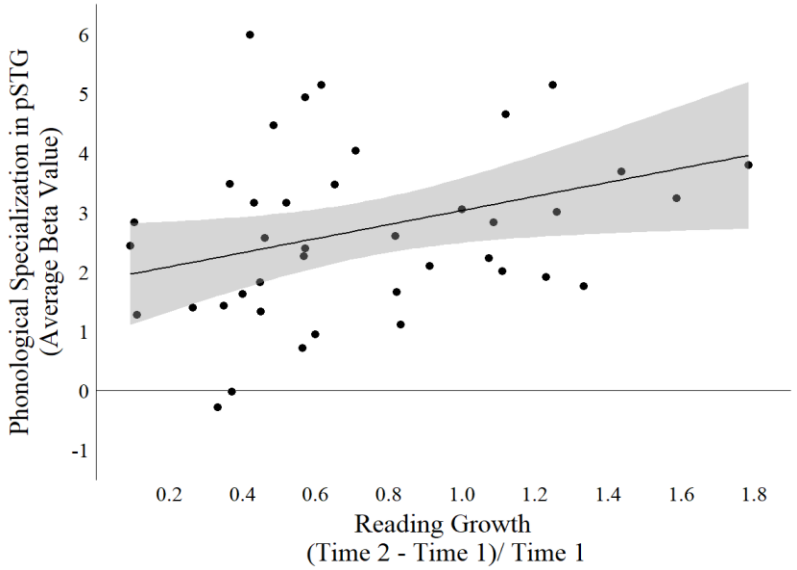
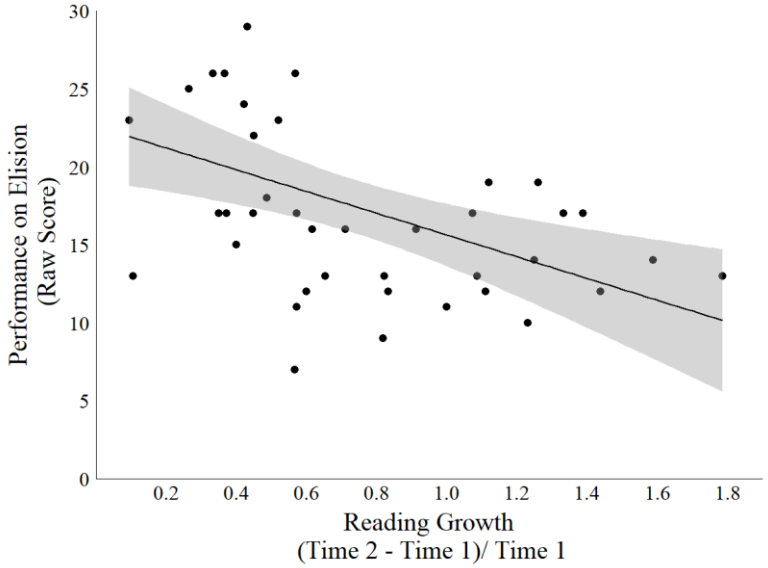


Figure 2

Relation between Performance on the Elision Subtest and Reading Growth.



Discussion

Results from the preregistered analyses demonstrated little to no evidence that individual differences in semantic and phonological skill (measured either behaviorally or neurally) reliably predicted reading growth. However, results from the exploratory analyses revealed decisive evidence in favor of the hypothesis that early phonological skills are predictive of later growth in reading skill. The best-fitting model was found to be the Brain-and-Behavior model, which explained 34% of the variance in reading growth. Within the Brain-and-Behavior model, a negative relation was observed between performance on the behavioral measure of phonological processing and reading growth ($\beta_{Elision}$ = -.48), which likely reflects that those who start with lower phonological (and reading) skills have more room to improve from 5-to-8 years old. Alternatively, a positive relation was observed between phonological neural specialization and reading growth ($\beta_{PhonSpecial}$ = .33). Prior work has shown that activation with the posterior superior temporal gyrus during phonological tasks is associated with lexical access to phonological representations (Graves et al., 2008). Therefore, the positive relation observed between phonological neural specialization and reading growth may reflect, consistent with the Interactive Specialization Theory, that more refined phonological representations facilitate growth in early word reading skills.

Understanding the factors that support and constrain reading development is critical given that reading represents a cognitive skill that is highly academically-relevant (e.g., Vineyard & Bailey, 1960) and essential to functioning in modern society (e.g., Raudenbush & Kasim, 1998). Consistent with previous behavioral work, results from the present study provide evidence that individual differences in early phonological skills are an important predictor of later growth in reading skill. These findings extend previous research and provide preliminary support for the Interactive Specialization Theory (Johnson, 2011) by demonstrating that the observed relation between phonological processing and reading growth may be driven by a process of neural specialization within the posterior superior temporal gyrus.

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