THE LONGITUDINAL RELATION BETWEEN THE NEURAL BASIS OF PHONOLOGICAL AWARENESS AND READING SKILL

By

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1. Background

Reading is the ability to map visual letters to sounds, which has been shown to be a strong predictor for academic success in school (Duncan et al., 2007). Understanding the mechanisms of reading acquisition and its predictors plays a fundamental role in reading education. The connectionist model of reading proposed by Seidenberg and McClelland (1989) argues that reading acquisition is a statistical learning process achieved by adjusting the weights and layers of connections among orthographic, phonological, and semantic representations. Phonological processing is a spoken language skill that is acquired before reading. By using computational simulation, Harm and Seidenberg (1999) found that training phonological representations leads to reading improvement, which we refer to as the scaffolding hypothesis. However, they also found that reading acquisition sharpened phonological representations, which we refer to as the sculpting hypothesis. Thus, there appears to be a reciprocal relation between phonological representations and reading skill. How the scaffolding and sculpting processes unfold in children during their development, however, remains less clear.

Phonological awareness, which is the ability to represent and access the sound structure of spoken words (Treiman & Zukowski, 1991), is one of the most frequently examined phonological skills. Consistent with the connectionist model, previous longitudinal studies found that children’s performance during phonological awareness tasks in kindergarten or preschool significantly predicted their reading skill when they were in the first or second grades (e.g., Perfetti et al., 1987; Bentin et al., 1993; Wagner et al., 1997; Hogan et al., 2005), supporting the scaffolding hypothesis. Only a few longitudinal studies examined the scaffolding effect in older children, but inconsistent evidence was found (Wagner et al., 1997; Hogan et al., 2005). For example, Wagner et al. (1997) showed that phonological awareness performance in the second grade continued to predict children’s reading skill when they were in the fourth grade, although the effect decreased. Hogan et al. (2005) did not show any scaffolding effect in children from first to third grade. Therefore, behavioral studies generally support the scaffolding hypothesis. However, this scaffolding effect appears to decrease or disappear as children grow older. In terms of the sculpting hypothesis, results are mixed for both young and older children. Some studies showed that earlier reading skill predicted later phonological awareness performance (e.g., Perfetti et al., 1987; Hogan et al., 2005; Boets et al., 2010), whereas others did not (e.g., Wagner et al., 1997). This discrepancy could be due to the different sensitivity of phonological awareness measures used. Thus, whether and when the sculpting effect occurs in developing children remained unclear.

Three factors in phonological awareness are likely to impact scaffolding and sculpting processes in developing children. First, grain size may play a role. Phonological awareness includes different grain sizes, ranging from small grain phonemic to larger grain rhyme or syllabic awareness. Children develop larger grain phonological awareness earlier than small grain phonemic awareness (Anthony, 2005). In contrast, during reading acquisition, the connectionist model suggests that regular words, which depend on transparent small grain letter-to-phoneme decoding, are acquired more quickly than irregular words. Decoding irregular words relies on larger grain orthography-to-phonology mapping and thus requires more complex computations. Consistent with this, Frith (1985) proposed a developmental theory of reading arguing that children's reading skill transitions from the alphabetic stage, using small grain letter-to-phoneme mapping, to the orthographic stage, employing larger grain orthography-to-phonology mapping. A few previous behavioral studies have examined grain size effects in children from kindergarten to 1st or 2nd grade. They have consistently found that the measures of phonemic awareness are stronger predictors of later reading skill than the measures of rhyme awareness (e.g., Muter, et al., 1998; Hulme et al., 2002; Muter et al., 2004; Castles & Coltheart, 2004), suggesting the importance of small grain size in young children. This finding aligns with the theory of reading development by Frith (1985) that beginning readers rely on small grain letter-to-phoneme mapping. However, to our knowledge, no studies have examined grain size effects on the scaffolding process in older children. In addition, no studies have investigated grain size effects on the sculpting process in either young or older children. Therefore, there is a significant gap in the literature in terms of how different grain sizes of phonological awareness influence scaffolding and sculpting processes in developing children. Addressing this question is important as it provides empirical evidence for a mechanism of reading development, which could provide constraints on the connectionist model of reading. Although the connectionist model simulated the processes of regular versus irregular word learning, which suggests grain size effects, directly incorporating the concept of grain size effects in the model to simulate reading development is novel.

The second factor that may affect scaffolding and sculpting processes in developing children is whether there is automatic orthographic activation during phonological awareness tasks. Based on the connectionist model, learning to read not only establishes a feedforward mapping from orthography to phonology, but also a feedback mapping from phonology to orthography. As a result of this feedback mapping, orthographic information can be automatically activated even during auditory phonological tasks. In support of the existence of a feedback mapping, many behavioral studies have shown an orthographic intrusion effect during phonological awareness tasks. For example, participants responded slower to inconsistent words such as *pie-rye* as compared to consistent words such as *pie-tie* in phonological awareness tasks. This effect was mainly observed in adults and older elementary children (Adults: Castles et al., 2003; Halle, Chereau and Segui, 2000; Seidenberg & Tanenhaus, 1979; Children: Landerl, Frith & Wimmer, 1996; Ziegler & Muneaux, 2007; Castles et al., 2003). Although young children who were beginning readers did not show the orthographic intrusion effect as an entire group, higher skilled readers within this group did show such an effect (Ziegler & Muneaux, 2007). Thus, behavioral studies suggest that automatic orthographic activation occurs early after reading acquisition, the strength of which seems to be influenced by children's reading skill. By examining brain activation in the left ventral occipitotemporal cortex (vOT), a region involved in representing visual word forms (Dehaene et al., 2005), neural studies provide a complementary way of detecting automatic orthographic activation during phonological awareness tasks. Along with behavioral findings, previous neural studies found that the left vOT was activated during auditory phonological awareness tasks and its activation strength was associated with children's reading skill (Raschle, et al., 2012; Wang, Joanisse, & Booth, 2018; Debska et al., 2016; Wang et al., 2021; Derosches et al., 2010; Debska et al., 2019). Thus, neural studies also support the existence of a feedback mapping from phonology to orthography during phonological awareness tasks.

Although previous behavioral and neural studies support automatic orthographic activation during phonological awareness tasks and suggest that this activation is related to reading skill, all of these studies are correlational. It is unclear what the causal relation is between reading skill and automatic orthographic activation. It is likely that learning to read initially establishes a link between orthography and phonology, resulting in automatic orthographic activation during phonological awareness tasks. Later on, as the feedback mapping from phonology to orthography becomes stronger, this feedback serves as a scaffold for later reading acquisition. Castles, Wilson and Coltheart (2011) has examined the temporal relation between automatic orthographic activation and reading in young children. They trained letter-sound correspondence in 4-year-old preschoolers who had no previous reading experience and found that children's phonemic awareness performance was significantly improved in trained items as compared to untrained items. The authors suggested that learning letter-sound correspondence likely provided orthographic representations for phonemes, resulting in improved task performance. However, because behavioral performance is a biproduct of multiple cognitive processes, we cannot rule out the possibility that learning to read sharpened phonological representations, which then led to children's elevated performance. Thus, it remains unclear if reading acquisition causes automatic orthographic representations during phonological awareness tasks. In addition, no studies have examined if the automatic orthographic activation during phonological awareness tasks in turn serves as a scaffold for reading acquisition later in development. These two questions are important to address, because they provide additional constraints on the connectionist model of reading. Previous examinations of this model focused on how the activation of orthographic representations through visual input is related to reading acquisition (e.g., Seidenberg, 1992; Cunningham et al., 2010; Centanni, et al., 2019). How the feedback mapping from phonology to orthography and the automatic orthographic activation with auditory input play a role in reading acquisition has not been examined.

The third factor that may influence scaffolding and sculpting processes in developing children is the nature of phonological representations versus access to those representations. Phonological awareness requires two neural processes to interact: first, there must be the activation of phonological representations for the sound units in a word, and secondly, executive mechanisms are required to direct retrieval of such information in a task-appropriate way. Thus, both the quality of phonological representations and the effectiveness of accessing those representations contribute to phonological awareness performance. Previous literature has suggested that dyslexia is best described as a core phonological deficit (Snowling, 1998). However, whether children with dyslexia have deficits in phonological representations or accessing those representations is debated (e.g., Boada & Pennington, 2006; Ramus & Szenkovits, 2008). Part of the reason for this debate is that access to phonological representations is unlikely to be clearly dissociated from representations in a phonological task using behavioral measures. Brain measures provide a valuable approach to help dissociate these two processes by examining two separate brain regions. According to the memory, unification, and control model by Hagoort (2016), regions in the temporal cortex contain the knowledge representations that have been laid down in memory during acquisition. Frontal regions (Broca's area and the adjacent cortex) are crucial for unification operations where composition and decomposition can occur. Consistent with this model, previous studies suggest that the posterior part of the left superior temporal gyrus (STG) is associated with representing the acoustic and perceptual features of phonology (Myers et al., 2009; Leonard & Chang, 2014), whereas the left dorsal inferior frontal gyrus (IFG) is associated with accessing and operating on the phonological representations stored in STG (Myers et al., 2009; Boets, et al., 2013). Thus, by examining the brain activity in the left STG and IFG during phonological awareness tasks, we can address the on-going debate about whether it is the phonological representations themselves or access to those representations that is associated with reading skill.

Several previous studies have examined brain activation during phonological awareness tasks and its relation to children's reading skill. Brain activation in the left STG during phonological tasks was frequently found to be correlated with reading skill in young children (5-6 years old in Raschle et al., 2012 and Luniewska et al., 2019; 6-7 years old in Debska et al., 2016; 5-8 years old in Chyl et al., 2018; 8 years old in Vandermosten et al., 2019). However, brain activation in the left IFG during phonological tasks was often found to be associated with reading skill in older elementary children or adults (10-13 years old in Corina et al., 2001; 9 years old in Heim et al., 2010; 10-12 years old in Cao et al., 2017; adults in Boets et al., 2010). Thus, there appears to be a developmental progression from STG to IFG that is related to reading skill. This developmental progression is consistent with a language development theory in which it is argued that processes in the frontal lobe mature later than those in the temporal lobe (Skeide & Friederici, 2016). However, all of these previously mentioned neural studies were correlational and thus unable to address the directionality of the relation between reading and phonological processing.

Only two previous neural studies used a longitudinal design to address the causal relation (Mauer et al., 2009; Yu et al., 2020). They consistently found that brain activation in the posterior left STG during a phonemic task or an onset judgement task in kindergarteners was predictive of children's later reading skill. These results suggest that the quality of phonological representation serves as a scaffold for later reading acquisition in young children. However, both studies did not control for initial reading skill and only examined brain activity in young children. It is unclear whether the scaffolding effect was due to the autoregressive effect and unclear whether phonological access in the frontal lobe would serve as a scaffold for later reading in the development of older children. In addition, none of the longitudinal neural studies examined the sculpting hypothesis. Therefore, how the processes of scaffolding and sculpting depend on phonological representation versus access in developing children is unknown. Addressing this question is important because it can promote the understanding of phonological deficits in dyslexia. Moreover, this study further constrains a prominent reading model. Only phonological representations are included in the connectionist model to account for reading acquisition. A recent computational model for semantic cognition has already incorporated both semantic representation and control elements to provide a wide-ranging and neurally plausible account of normal and impaired semantic cognition (Hoffman et al., 2018). In their model, the control element is a top-down retrieval process that helps amplify weak/ambiguous semantic relationships through iterative feedback given the information of the probe. With this element added, their model can reproduce the behavioral patterns of patients with semantic dementia and semantic aphasia during semantic tasks. Because previous studies indicate that children at different ages may rely on different brain regions during phonological processing as a function of reading skill, neural studies on how the processes of scaffolding and sculpting depend on phonological representation versus access will need to be incorporated into connectionist models to better account for the mechanism of reading.

2. Aims of my dissertation

My dissertation aimed to examine how the scaffolding and sculpting processes unfolded during development and were affected by three factors namely (1) grain size, (2) automatic orthographic activation, and (3) representation versus access. Studying these questions can directly address the hypotheses generated from the connectionist model of reading and may require modifications to this model by incorporating control processes. In addition to the theoretical contribution, the findings from my dissertation have concrete implications for educational practice in reading in terms of deciding (1) what grain sizes of phonology should be trained at different ages, (2) if training the mapping between sounds and letters is more helpful than purely training sounds, and (3) what component of phonological skills (i.e., representational quality or accessing efficiency) is critical to train at different ages.

All the data used in my dissertation was from a publicly available dataset shared on OpenNeuro.org (see detailed description in Wang et al., 2022). Woodcock Johnson Letter-Word Identification, a standardized test in which participants were asked to read out loud printed letters and words was used as a behavioral measure of children's reading skill. A functional magnetic resonance imaging (fMRI) task on sound judgement was used as a brain measure of phonological awareness. In the sound judgement fMRI task, children were asked to judge whether the two auditory words they heard sequentially share any of the same sounds or not. Both small (i.e., onset) and large (i.e., rhyme) grain phonological awareness conditions were included, allowing for the examination of grain size effects. This dataset includes three sessions of testing, i.e., ses-5, ses-7, ses-9. Children were approximately 5.5-6.5 years old when they attended ses-5, 7-8 years old when they attended ses-7, and 9-10 years old when they attended ses-9. Because the number of children having three completed sessions is low, data were divided into two longitudinal cohorts, namely, a cohort of young beginning readers from ses-5 to ses-7 and another cohort of older elementary children from ses-7 to ses-9. These two cohorts allowed for the examination of developmental changes. Two sets of studies were conducted, both of which examined the influence of age and grain sizes on the scaffolding and sculpting processes.

3. Two sets of studies

3.1. The longitudinal relation between reading skill and automatic orthographic activation

3.1.1. Introduction

The first set of studies (study 1 & 2) examined the bidirectional relation between reading skill and automatic orthographic activation during the phonological awareness task in young and older children. Brain activation in the left vOT was used as an index for automatic orthographic activation during the phonological awareness task. The functional connectivity between the left STG and vOT was used as an index for the effectiveness of the connection between phonological and orthographic representations. According to the local combination detector model by Dehaene et al. (2005), the left vOT has a hierarchical structure with the posterior part sensitive to small grain orthography such as letters, whereas the anterior part is sensitive to larger grain orthography such as bigrams or trigrams. Thus, I examined the anterior and posterior vOTs during onset or rhyme processing separately to examine the grain size effects.

Figure 1 shows my hypotheses for the first sets of studies. The connectionist model predicts that the feedback mapping between orthography and phonology should be initially established as a result of learning to read, and over development it should in turn facilitate reading acquisition. Thus, I expected that young children would only exhibit the sculpting effect, whereas older children would show the sculpting and scaffolding effects. In terms of the grain size effect, based on a developmental theory of reading (Frith, 1985), I predicted that the sculpting effect would be on small grain orthography in the posterior vOT in young children but on large grain orthography in the anterior vOT in older children. In addition, I predicted that if the scaffolding effect appeared in older children, larger grain automatic orthographic activation would be more likely to play a role than small grain automatic orthographic activation.

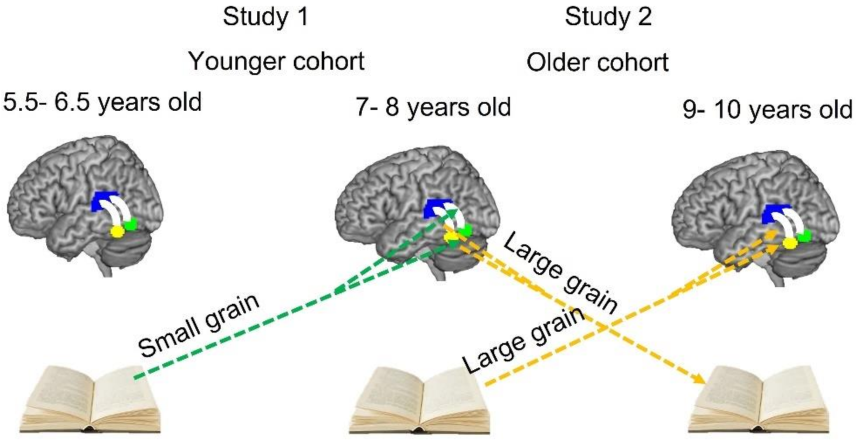

Figure 1. Predictions for the first sets of studies. Study 1 was on the younger cohort ages from ses-5 (i.e., 5.5-6.5 years old) to ses-7 (i.e., 7-8 years old) using brain activation and functional connectivity analyses. Study 2 was conducted on the older cohort ages from ses-7 (i.e., 7-8 years old) to ses-9 (i.e., 9-10 years old) using brain activation and functional connectivity analyses. The posterior left STG is colored in blue. The anterior left vOT is colored in yellow and the posterior left vOT is colored in green. Functional connectivity between brain regions is colored in white.

3.1.2. Method

Participants

For the younger cohort, 40 monolingual English-speaking children (25 girls, mean age = 5.7, SD = 0.3, range 5.0-6.3 years-old at T1, mean age = 7.3, SD = 0.2, range 7.1-8.0 years-old at T2) were included in our final analysis. For the older cohort, 61 monolingual English-speaking children (33 girls, mean age = 7.3, SD = 0.3, range 7.0-8.2 years-old at T1, mean age = 9.2, SD = 0.2, range 9.0-9.9 years-old at T2) were included in the final analysis. There were 18 participants that overlapped in the two cohorts. All children were recruited from the Austin, Texas metropolitan area. Informed consent form was obtained from parents. The Institutional Review Board approved all the procedures. Detailed description of data collection procedure, task design, and parameters can be found in our published data descriptor (Wang et al., 2022).

Exclusion criteria

All the children met the following criteria: (1) Primarily right-handed, defined as performing at least 3 out of 5 items using their right hand when they entered the project; (2) Mainstream English speakers, classified by the Language Variation Status sub-test on the DELV (Seymour et al., 2003); (3) No diagnosis of attention deficit hyperactivity disorder (ADHD), neurological disease, psychiatric disorders, learning or language disorder as reported in the developmental history questionnaire completed by their parents; (4) Normal hearing and normal or corrected-to-normal vision as reported by their parents; (5) No less than a standard score of 70 on KBIT-2 non-verbal subtest (Kaufman & Kaufman, 2004) and CELF-5 core language scale (Wiig, et al., 2013) at the first time point; (6) Acceptable accuracy and no response bias in the fMRI task. Acceptable accuracy was defined as the accuracy of the perceptual control and rhyme conditions being greater than or equal to 50% to be confident that the children were engaged in the task. The lack of a response bias was indicated by the accuracy difference between rhyme and unrelated conditions being no greater than 40%. (7) Good movement as indicated by no more than 10% or 6 consecutive outlier volumes in each run. The outlier volumes are defined as those with volume-to-volume head movement exceeding 1.5 mm in any direction, or deviations of more than 4% from the mean global signal.

Data analysis

The raw scores of the Letter-Word Identification subtest (word ID) on the Woodcock-Johnson III Test of Achievement (WJ-III, Woodcock et al., 2001) was used as a measure of reading accuracy. In this test, children were required to read out loud the presented letters and words with increasing difficulty (i.e., longer words and lower frequency).

The auditory phonological judgment task was an event-related design. Figure 2 illustrates a description of the task procedure. During each trial, children heard two auditory stimuli presented sequentially and binaurally through earphones. There were four conditions of the pairs of stimuli: onset, rhyme, unrelated, and perceptual (frequency modulated noise), examples of which can be seen in Table 1. Participants were asked, “do the two words share the same sound”. They were instructed to respond to all trials as quickly and accurately as possible with the right index finger indicating a yes response in the onset, rhyme and perceptual conditions, and the right middle finger for a no response in the unrelated condition. A blue circle remained on the screen during the auditory stimuli presentation, and it turned to yellow 1000ms before the trial ended to remind participants to respond. The duration of each word was between 500 and 700 ms followed by a brief period of silence, with the second word beginning 1000ms after the onset of the first. The duration of the response interval was 1800ms. There were 24 trials for each of the four conditions, divided into two runs. The four conditions were pseudo-randomized so there were no more than 5 of the same responses in a row. To aid in convolving the hemodynamic response, inter-trial intervals were jittered by randomly adding 0, 450 or 900ms for each trial, in equal proportions for the first run. For the second run, jitters of 0, 375 or 750ms were similarly added to the trials. Each run lasted about 3 minutes.

Table 1. Examples of the stimuli in the auditory phonological judgment task

Condition	Response	Brief Explanation	Example
Onset	Yes	The two words **start** with the same sound	Coat -- Cup
Rhyme	Yes	The two words **rhyme**	Wide -- Ride
Unrelated	No	The two words have no same sounds	Zip -- Cone
Perceptual	Yes	Frequency modulated noise	"Sh -- Sh"

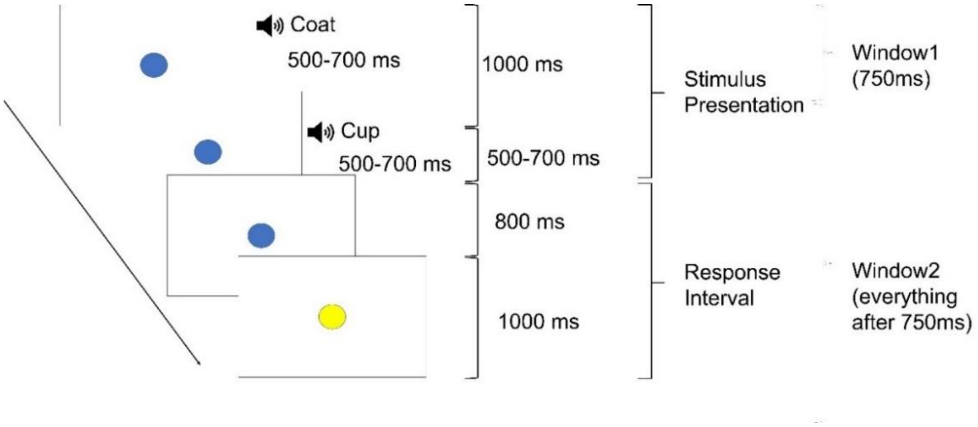

Figure 2. Example of a trial during the Sound Task.

fMRI data was pre-processed, and first-level modeled using a standard pipeline in the lab (see details from my previously published papers e.g., Wang, Joanisse, & Booth, 2020, 2021, Wang, Pines, Joanisse, & Booth, 2021). Here, smoothing was applied with 4-mm isotropic Gaussian kernel*[1]. In terms of defining regions of interest (ROI), we selected the classical visual word form area coordinate (-46 -53 -20 in MNI)

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[1] I used 4-mm instead of 6-mm smoothing kernel because the vOT ROIs were small. This 4-mm smoothing kernel was also used in Wang, Joanisse, & Booth (2021) when examining the concurrent correlation between vOT's activation and reading skill at different grain sizes. Both 4-mm and 6-mm smoothing kernel were tested, and the effects stayed the same in Wang et al., (2021).

from McCandliss et al. (2003) and the letter sensitive region coordinate (-36, -68, -12 in MNI) from Dehaene et al. (2004) as the centers for the anterior and the posterior vOT and then drew spheres around them with a radius of 7.5 mm. In this way, we created two adjacent anterior and posterior left vOT as our regions of interest without overlap, which should be sensitive to either bigrams/trigrams or letters (see Figure 1). In addition, we selected the posterior half of STG with y < -24 (Hickok & Poeppel, 2000) as our region of interest for phonological representation (also see Figure 1). This ROI was also used in studies 3 & 4, which examined the relation between reading skill and phonological processing during phonological awareness tasks (Wang, Joanisse, & Booth, 2020; Wang, Pines, Joanisse, & Booth, 2021). All the analyses focused on the left hemisphere of the brain.

Brain activation from the top 100 most activated voxels within the posterior vOT for the contrast of onset > rhyme for each individual was extracted as the index of the strength of automatic orthographic activation at small grain sizes. Brain activation from the top 100 most activated voxels within the anterior vOT for the contrast of rhyme> onset at each time point for each individual was extracted as the index of the strength of automatic orthographic activation at large grain sizes. We used the contrasts of onset versus rhyme because both conditions required a “yes” response and only differed in grain sizes. In addition, the general Psychophysiological Interaction (gPPI, McLaren, et al., 2012) was used to model the functional connectivity between the left STG and vOTs as the index of the efficiency of mapping between phonology and orthography. PPI is an analytical approach that allows examination of functional connectivity between a seed region and target regions during an experimental condition. The top 100 most activated voxels within the left posterior STG mask for each individual were used as the seed region, and the top 100 most activated voxels in the anterior or posterior vOT was the target region. Functional connectivity for onset > rhyme in the posterior vOT was used as the index of the connectivity strength between phonological and orthographic representation at small grain sizes. In addition, functional connectivity for rhyme > onset in the anterior vOT was used as the index of the connectivity strength between phonological and orthographic representation at large grain sizes. Beta values associated with PPI effect for different grain sizes at each timepoint for each individual were extracted. To examine the scaffolding hypothesis, a hierarchical regression analysis was conducted by entering brain activity or functional connectivity at T1 as the predictor, non-verbal IQ and reading skill at T1 as the controlled variables and reading skill at T2 as the dependent variable. To examine the sculpting hypothesis, a hierarchical regression analysis was conducted by entering reading skill at T1 as the predictor, brain activity or functional connectivity at T1 as the control variables, and brain activity or functional connectivity at T2 as the dependent variable. All tests used Bonferroni correction to correct for multiple comparison of 2 models to determine significance.

3.1.3. Results*[2]

Younger cohort

The regression analysis which examined the scaffolding hypothesis showed that brain activation in the posterior vOT for small grain phonemic processing (onset > rhyme) at T1 did not significantly predict reading skill at T2 after controlling for the reading skill at T1 and nonverbal IQ. However, unexpectedly, brain activation in the anterior vOT for large grain rhyme processing (rhyme > onset) at T1 significantly predicted reading skill at T2 (*p* = 0.049, Bonferroni corrected) after accounting for the effects of the covariates of no interest (see Table 2).

Table 2. Results of the hierarchical regression analyses examining whether early brain activation in vOT predicted later reading skill in the younger cohort (scaffolding hypothesis).

			Dependent measure					
			T2 Reading skill					
	Step	Predictor	B	R^2	ΔR^2	B	R^2	ΔR^2
Model		T1 Nonverbal IQ	-.017			-.017		
1	1	T1 Reading skill	.799***	.628		.799***	.628	
Model		T1 Nonverbal IQ	-.015			-.073		
2	1	T1 Reading skill	.791***			.867***		
	2	T1 Onset>Rhyme in posterior vOT	-.074	.634	.006			
	2	T1 Rhyme>Onset in anterior vOT				.235*	.679	.051

* $p < .05$, *** $p < .001$, Bonferroni corrected.

Figure 3A shows the scatterplot for the relation between brain activation for rhyme > onset in the anterior vOT at T1 and the standardized residual of reading skill at T2 after controlling for T1 reading skill and IQ. As is shown in the figure, the more brain activation in the anterior vOT that was specialized for large grain size representation, the better children's later reading skill. Because we used a contrast between rhyme and onset, the effect could be driven by more engagement of rhyme, less engagement of onset or both. To address this problem, we separately looked at the relation between brain activation for rhyme at T1 and the standardized residual of reading skill T2 (See Figure 3B), and the relation between brain activation for onset at T1 and the standardized residual of reading at T2 (See Figure 3C). Figure 3B and 3C shows that the scaffolding effect was mainly driven by greater specialization of the anterior vOT for large grain sizes (i.e., an increase of brain activation for rhyme and a slight decrease of brain activation for onset) at T1.

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[2] For the sake of saving space, here I only display the significant findings. The full results can be found in a manuscript revision re-submitted to Developmental Sciences. The manuscript is available upon request.

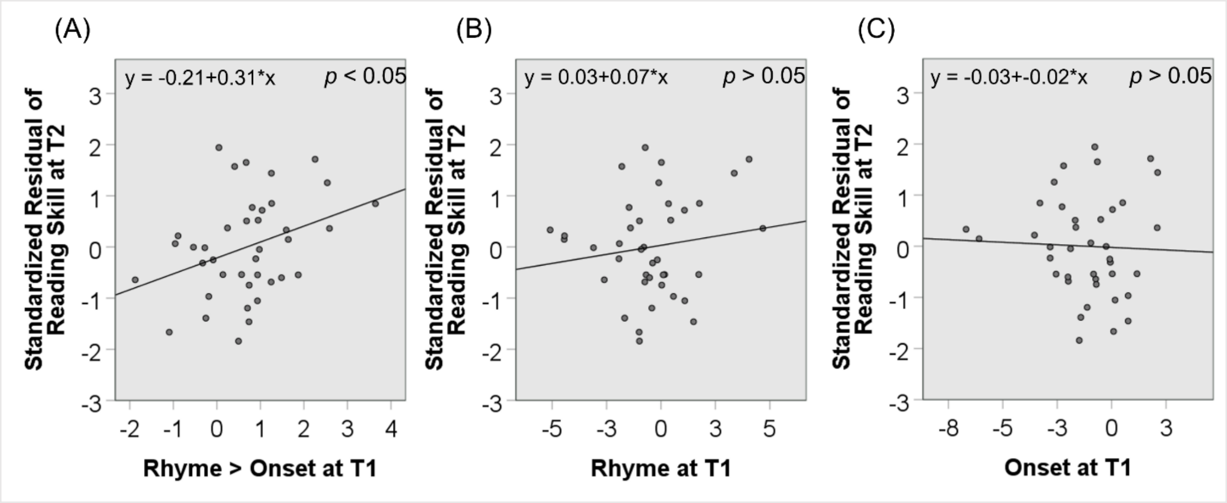

Figure 3. The scatterplots of early brain activation in vOT with later reading skill in the younger cohort. (A) The scatterplot for the relation between brain activation for Rhyme > Onset at T1 and the standardized residual of Reading Skill at T2. (B) The scatterplot for the relation between brain activation for Rhyme at T1 and the standardized residual of Reading Skill at T2. (C) The scatterplot for the relation between brain activation for Onset at T1 and the standardized residual of Reading Skill at T2.

The regression analysis which examined the sculpting hypothesis showed that reading skill at T1 significantly predicted functional connectivity between STG and the posterior vOT for small grain phonemic processing (onset > rhyme) at T2 (*p* = 0.014, Bonferroni corrected) after controlling for functional connectivity at T1 and nonverbal IQ. However, we did not find that reading skill at T1 predicted functional connectivity between STG and the anterior vOT for large grain rhyme processing (rhyme > onset) at T2 after accounting for the effects of the covariates of no interest (See Table 3).

Table 3. Results of the hierarchical regression analyses examining whether early reading skill predicted later functional connectivity between STG and vOT in the younger cohort (sculpting hypothesis).

			Dependent measures					
			T2 Onset > Rhyme connectivity			T2 Rhyme > Onset connectivity		
	Step	Predictor	B	R^2	ΔR^2	B	R^2	ΔR^2
Model 1	1	T1 Nonverbal IQ	.206			.007		
		T1 Onset>Rhyme connectivity	.051	.042				
		T1 Rhyme>Onset connectivity				-.191	.037	
Model 2	1	T1 Nonverbal IQ	.011			.011		
		T1 Onset>Rhyme connectivity	.041					
		T1 Rhyme>Onset connectivity				-.189		
	2	T1 Reading skill	**.470***	**.225**	**.183**	-.009	.037	.000

Figure 4A shows the scatterplot for the relation between reading skill at T1 and the standardized residual of functional connectivity between STG and the posterior vOT for onset > rhyme at T2. As is shown in the figure, the better the reading skill that children had at T1, the more specialized the functional connectivity between STG and the posterior vOT for the small grain phonemic processing was at T2. Because we used a contrast between onset and rhyme, the effect could be driven by stronger functional connectivity for rhyme, weaker functional connectivity for onset or both. To address this question, we separately looked at the relation between reading skill at T1 and the standardized residual of functional connectivity for rhyme at T2 (See Figure 4B), and the relation between reading skill at T1 and the standardized residual of functional connectivity for onset at T2 (See Figure 4C). Figure 4B and 4C shows that the sculpting effect was driven by greater specialization of functional connectivity between STG and the posterior vOT for small grain sizes (i.e., an increase of functional connectivity for onset and a slight decrease of functional connectivity for rhyme).

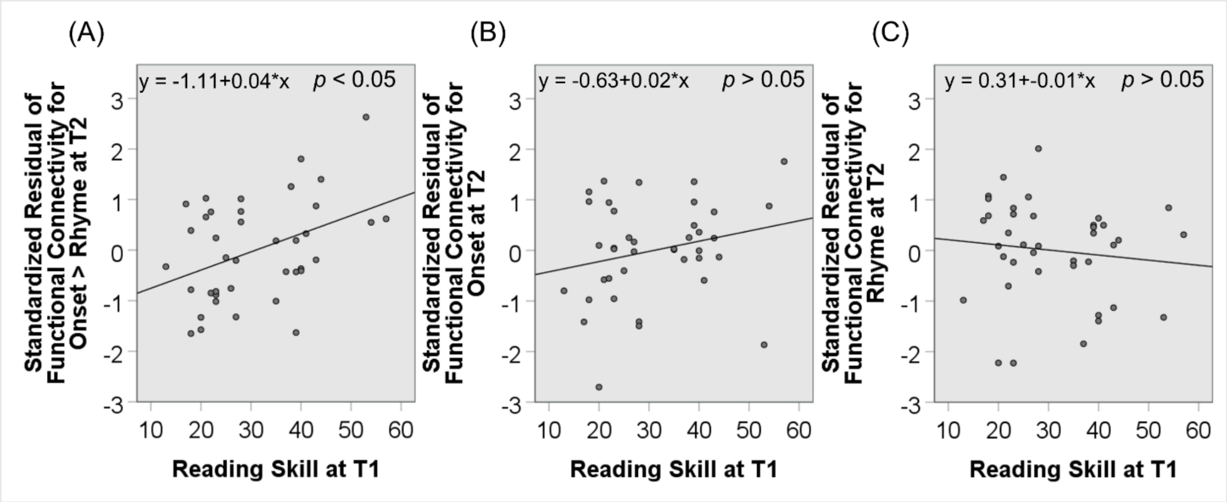

Figure 4. The scatterplots of early reading skill with later functional connectivity between STG and vOT in the younger cohort. (A) The scatterplot for the relation between reading skill at T1 and the standardized residual of functional connectivity for Onset > Rhyme at T2. (B) The scatterplot for the relation between reading skill at T1 and the standardized residual of functional connectivity for Onset at T2. (C) The scatterplot for the relation between reading skill at T1 and the standardized residual of functional connectivity for Rhyme at T2.

Older cohort

No significant findings were observed.

3.1.4. Discussion

Study 1 & 2 aimed to examine the relationship between reading skill and automatic orthographic activation during phonological awareness. We found that in the younger cohort when children were about 6 to 7.5 years old, earlier reading skill predicted later functional connectivity between the left posterior STG and the left posterior vOT for small grain sizes (i.e., onset), supporting the sculpting hypothesis. In addition, we found that in the younger cohort, earlier brain activation in the anterior vOT for large grain sizes (i.e., rhymes) predicted later reading skill, suggesting a scaffolding effect. However, in the older cohort when children were about 7.5 to 9 years old, we did not find either scaffolding or sculpting effects. These findings are summarized in Figure 5.

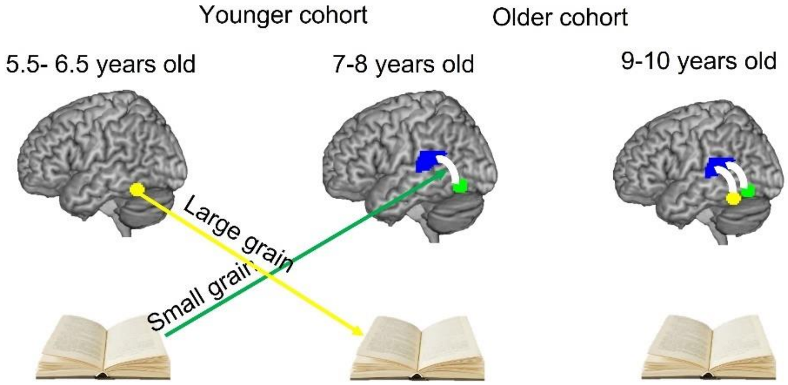

Figure 5. Results from the study 1 & 2 on the relationship between reading skill and automatic orthographic activation for both the younger and older cohort. In the younger cohort, earlier reading skill sculpted later functional connectivity from phonemes to letters at small grain sizes and earlier brain activation for large grain sizes scaffolded later reading skill. There were no scaffolding or sculpting effects for older children.

The finding of a sculpting effect in young children was as expected because the connectionist model of reading (Seidenberg & McClelland, 1989) predicts that reading drives the connection between orthography and phonology, resulting in a strengthened connection from phonological to orthographic representations during spoken language processing. In addition, according to the phase theory of reading (Frith, 1985, Ehri, 2020), young children who are beginning readers likely rely on small grain letter-to-phoneme mapping. Thus, when the sculpting effect occurs in young children, it should influence small grain phoneme-to-letter mapping. Consistent with these hypotheses, our study showed that, in beginning readers who were 6 to 7.5 years old, better initial reading skill predicted stronger functional connectivity between the left STG and the left posterior vOT for small grain phonemic processing. This effect was specific for small grain sizes as we did not find that earlier reading predicted later functional connectivity between the left STG and the left anterior vOT for large grain rhyme processing. Overall, these findings provide the first neural evidence for how reading sculpts the automatic engagement of orthographic representations.

Although we found the expected sculpting effect using functional connectivity measures, we did not find one using brain activation measures. Brain activation and functional connectivity reflect different processes (e.g., Gerchen & Kirsch, 2017). Functional connectivity mainly reflects the effectiveness of communication between regions, whereas brain activation is associated with engagement of representations in one region. Our functional connectivity results suggest that better reading skill at 6 years old can enhance later effectiveness of mapping from phonemes to letters in the brain at 7.5 years old. However, it does not necessarily mean that better earlier reading skill will increase children's later engagement of letter representations in the left posterior vOT while performing phonemic judgements. Children may rather engage representations directly related to the performance on the tasks. According to a previous study (Wang, Joanisse, & Booth, 2021), 7.5-year-old children relied on their refined phonemic representations in the left superior temporal gyrus to perform the onset judgement task. Improved effectiveness of mapping from phonemic to letter representations likely serves as a foundation for an ease of engaging letter representations. When a phonemic judgement task becomes more difficult and having letter representations of auditory words becomes important for performing tasks, say, if the shared phoneme of two auditory words is in the final or middle rather than at the onset location (Treiman et al., 1993), better reading will likely be related to both more effective functional connectivity between phonemic and letter representations and greater brain activation in the left posterior vOT. Future studies are needed to examine this hypothesis.

In addition to the sculpting effect, we observed some evidence for a scaffolding effect in young children. We found that brain activation in the anterior vOT for large grain size scaffolded later reading skill. This was not predicted because 6-year-olds were expected to be too young to establish an effective phonology-to-orthography mapping that could allow for automatic orthographic activation. Consistent with this argument, scaffolding was not supported by the findings that later reading skill was related to earlier functional connectivity between the left STG and the left anterior vOT for small or large grain size, or brain activation in the posterior vOT for small grain size. However, the 6-year-olds included in our study generally had higher language and reading skills than their age-matched peers. Therefore, they might have developed some level of visual-sound connections before they could decode words. We speculate that the limited scaffolding effect for activation during large grain processing may reflect the engagement of holistic visual representations for auditory words that are non-linguistically structured.

Young children are frequently exposed to rhyming words in picture book reading (Read, Macauley, & Furay, 2014). This may encourage them to establish automatic activation of visual words at a pre- and partial-alphabetic stage when listening to language (Ehri, 2020). At this stage, children tend to rely on visual salience or context cues to read. Previous research has shown that young children perceive rhymes in a global way, and with reading development, their perception of rhymes becomes more analytical and fine-grained (Cardoso-Martins, 1994). Therefore, it is possible that young children are accessing visual rimes that corresponds to auditory rhymes in a holistic way, and with more experience they acquire the alphabetic principle. Although young children are learning to use small grain letter-to-phoneme mapping in visual word decoding (Frith, 1985), their sensitivity of spoken words biases them towards auditory rhymes earlier than phonemes. Our current finding of a scaffolding effect suggests that automatic activation of visual representations during rhyme processing play an important role in reading acquisition. That is, the more children engage holistic representations at large grain sizes during spoken word processing, the better they will learn to read. This finding informs educational practice, suggesting that even when children are unable to decode words, providing visual representations in books with rhyming will likely facilitate later reading acquisition. This is consistent with previous literature has shown that children's pre-literate early rhyming skills predict later reading development (Bryant, MacLean, Bradley, 1990; Wood & Terrell, 1998; Goswami & Bryant, 2017).

In contrast to the findings in young children, we did not observe either a scaffolding or sculpting effect in older children ages 7.5 to 9 years old. Typical children learn to decode accurately first, and then become fluent with practice (Norton, &Wolf, 2012), so fluency may play a more important role than accuracy in reading acquisition in older children. Our use of a reading accuracy skill measure may account for its lack of relation in older children to the automatic activation in vOT or the functional connectivity of the STG with vOT. Previous studies support this idea by showing that reading accuracy plays a role in the automatic activation of vOT in younger children or those with lower reading skills (Wang, Joanisse, & Booth, 2018; Desroches et al., 2010). However, in older children, fluency of reading words or letters tends to be associated with automatic activation in vOT (Debska et al., 2019; Wang, Joanisse, & Booth, 2021). Future longitudinal neuroimaging studies measuring reading fluency are needed to examine if the scaffolding and sculpting effects occur in older children.

To sum up, study 1 & 2 aimed to determine how the mapping from phonology to orthography, as well as the automatic activation of orthographic representations, during phonological awareness was related to reading acquisition in developing children at different ages. Consistent with prevailing reading models that learning to read strengthens the connections between phonology and orthography, we showed that early reading skill was associated with the sculpting of later functional connectivity between phonemes and letters when making auditory phonological judgments. Unexpectedly, we found that activation of large grain visual representations for auditory rhymes in younger children was associated with later reading skill. This finding suggests that there may be an important role of automatic visual representations for auditory rhymes in early reading acquisition, but that may be holistic and non-linguistically structured. Finally, we observed no scaffolding or sculpting effects when examining reading accuracy in older children, so future studies should examine reading fluency.

3.2. The longitudinal relation between reading skill and phonological processing

3.2.1 Introduction

The second set of studies (study 3 & 4) investigated the bidirectional relation between reading and two phonological processes in young and older children. Two steps of brain analyses were conducted. The first step of analyses was using univariate analyses. Brain activity in the posterior left STG and dorsal left IFG was used to index the engagement of phonological representation and access, respectively. In addition, functional connectivity between the dorsal left IFG and the posterior left STG was used to index the effectiveness of IFG accessing phonological representations stored in STG.

The second step of analyses involved a multi-voxel pattern analysis (MVPA). This approach allowed us to determine how brain activation patterns in STG can differentiate various grain sizes of phonology by calculating a decoding coefficient. Traditional univariate fMRI analysis treats each voxel as an independent piece of data and uses statistical tests to determine whether that voxel responds more in some experimental conditions than in others. However, this approach loses information in voxels that are weakly activated but related to each other to support the precision of phonological representations. MVPA extracts information contained in the patterns of activity among multiple voxels to obtain information of the relative differences in activity between voxels (Tong & Pratte, 2012). Therefore, MVPA may be more sensitive than the univariate analysis in detecting the quality of phonological representations stored in the left posterior part of the left STG.

Figure 6 shows my hypotheses for the second set of studies. The neurocognitive model of language (Skeide & Friederici, 2016) and previous neural literature suggest a developmental progression from the temporal to the frontal lobe during phonological awareness tasks that are associated with reading skill. Thus, I expected that in young children, scaffolding and sculpting processes would rely more on phonological representation in the posterior left STG. In older children, phonological access in the dorsal left IFG would play a more important role. In terms of grain size effects, I expected that small grain size would play a role earlier than large grain size in the scaffolding effect as reading progresses from small to large grain size (Frith, 1985). However, because reading helps in the discovery of phonemes (Ziegler & Goswami, 2005), the sculpting effect should always involve small grain phonology.

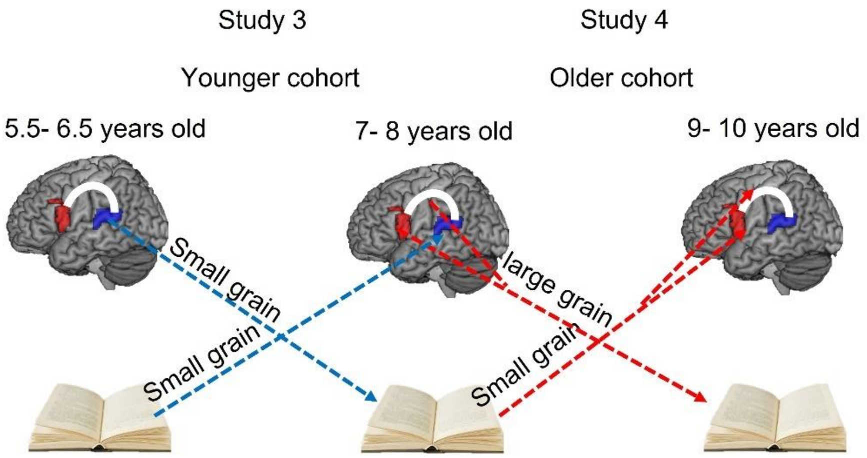

Figure 6. Predictions for the second sets of studies. The younger cohort refers to children who were measured at both ses-5 (5.5-6.5 years old) to ses-7 (7-8 years old). The older cohort refers to children who were measured at both ses-7 (7-8 years old) and ses-9 (9-10 years old). The posterior left STG is colored in blue. The dorsal left IFG is colored in red. Connectivity between brain regions is colored in white.

3.2.2 Method

3.2.2.1 Analysis 1 -using univariate analyses *[3]

Participants

For the younger cohort, 36 children (19 girls, mean age = 5.9, range 5.6-6.5 years old at Time 1, mean age =7.5, range 7.1-8.2 years old at Time 2) were included in this study. This is different from the studies 1 & 2 because we used slightly different criteria. One difference is that we set a criterion of no less than a standard score of 80 (instead of 70) on the KBIT-2 non-verbal subtest and CELF-5 core language scale at the first time point. The other difference is that acceptable accuracy was defined as the accuracy of the perceptual control and rhyme conditions being greater than 50% (instead of including 50%) to be confident that the children were engaged in the task. Three participants were excluded due to these two criteria. One participant was excluded because they did not have frontal coverage in the functional image.

For the older cohort, 59 monolingual English-speaking children (32 females, mean age = 7.3, range 7.0-8.2 years old at Time 1, mean age = 9.2, range 9.0-9.9 years old at Time 2) were included in this study. This is different from study 1 & 2 because acceptable accuracy was defined as the accuracy of the perceptual control and rhyme conditions being greater than 50% (instead of including 50%) to be confident that the children were engaged in the task.

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[3] Published work using univariate and functional connectivity analyses (Wang, Joanisse, & Booth, 2020; Wang, Pines, Joanisse, & Booth, 2021).

Data Analysis

fMRI data was pre-processed, and the first level modeled using a standard pipeline in the lab (see details from my previously published papers e.g., Wang, Joanisse, & Booth, 2020, 2021, Wang, Pines, Joanisse, & Booth, 2021). Smoothing was applied using a 6-mm isotropic Gaussian kernel. In terms of defining ROI, we used the opercular part of the left IFG and the left posterior STG ($y < -24$) as our anatomical masks.

Brain activation from the top 100 most activated voxels within the left posterior STG and the opercular part of the left IFG for the contrast of onset > perceptual and rhyme> perceptual at each time point for each individual was extracted. Brain activation within the left posterior STG was used as the index of the engagement of phonological representation. Brain activation within the left IFG was used as the index of the engagement of phonological access. In addition, the general Psychophysiological Interaction (gPPI) was used to model the functional connectivity between the left IFG and STG as the index of the effectiveness of IFG accessing phonological representations stored in STG. The top 100 most activated voxels within the left IFG mask for each individual were used as the seed region, and the top 100 most connected voxels in the left STG were the target regions. Functional connectivity for onset > perceptual and rhyme > perceptual at each timepoint for each individual was then extracted. To examine the scaffolding hypothesis, a hierarchical regression analysis was conducted by entering brain activity or functional connectivity at T1 as the predictor, non-verbal IQ and reading skill at T1 as the controlled variables and reading skill at T2 as the dependent variable. To examine the sculpting hypothesis, a hierarchical regression analysis was conducted by entering reading skill at T1 as the predictor, brain activity or functional connectivity at T1 as the control variables, and brain activity or functional connectivity at T2 as the dependent variable.

3.2.2.2 Analysis 2-using multivariate analyses

Participants

The same as study 1 & 2.

Data analysis

I used a correlational MVPA approach, adopted from Haxby et al. (2001), to calculate the decoding coefficients for different grain sizes of phonological processing. fMRI data was firstly preprocessed with no smoothing applied. Then, a general linear model (GLM) at each time point for each run was modeled with the four task conditions (i.e., onset, rhyme, unrelated, perceptual) as regressors of interest and six movements as regressors of no interest. After that, three t-maps were generated using the contrasts of onset > perceptual, rhyme > perceptual, unrelated > perceptual to index word processing of different categories. The top 500 most activated voxels in the left posterior anatomical STG for the contrast of all words versus perceptual noise at each time point for each participant were selected as features of interest to perform MVPA*[4]. Figure 7 shows the overlap among participants of their top 500 voxels at each time point in both the young and older cohorts. Using the t values from the top 500 voxels, both the within- and across-category Pearson correlations were calculated across runs. After that, a decoding coefficient for each participant at each timepoint was calculated using the difference score between the within- and across-category Fisher-z transformed correlations, an approach also used in a previous paper by Vandermosten et al. (2020). The logic behind this calculation is that if a brain region can differentiate two categories with its activation pattern, the within-category correlations should be higher than the across-category correlations. Thus, the larger difference between the within- and across- correlations, the better this area can decode the targeted information. In my study, the decoding coefficient for onset versus unrelated processing was used as an index for the precision of small grain phonological representations. The decoding coefficient for rhyme versus unrelated processing was used as an index for the precision of large grain phonological representations.

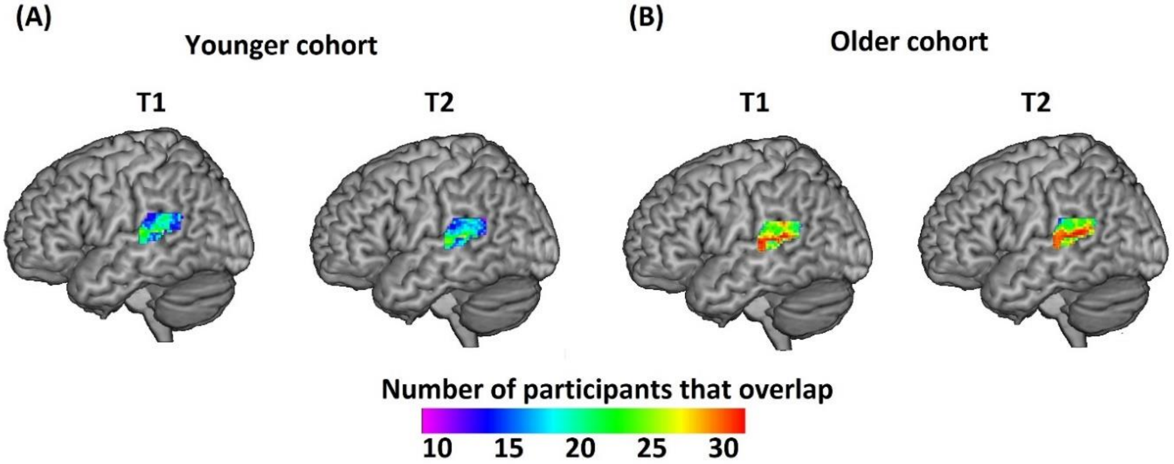

Figure 7. The overlap of individualized ROI among participants at each time point for MVPA. (A) younger cohort (B) older cohort.

To examine the scaffolding hypothesis, a hierarchical regression analysis was conducted by entering decoding coefficients for onset versus unrelated or rhyme versus unrelated at T1 as the predictor, with nonverbal IQ and reading skill at T1 as controlled variables. Reading skill at T2 was entered as the dependent variable. To examine the sculpting hypothesis, a hierarchical regression analysis was conducted by entering decoding coefficients for onset versus unrelated or rhyme versus unrelated at T2 as the dependent variable, reading skill at T1 as the predictor, with nonverbal IQ and brain decoding coefficients at T1 as controlled variables.

3.2.3 Results

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[4] We also used top 250 voxels as the feature of selection for MVPA. The result patterns remained the same.

3.2.3.1 Results from analysis 1 using univariate analyses*[5]

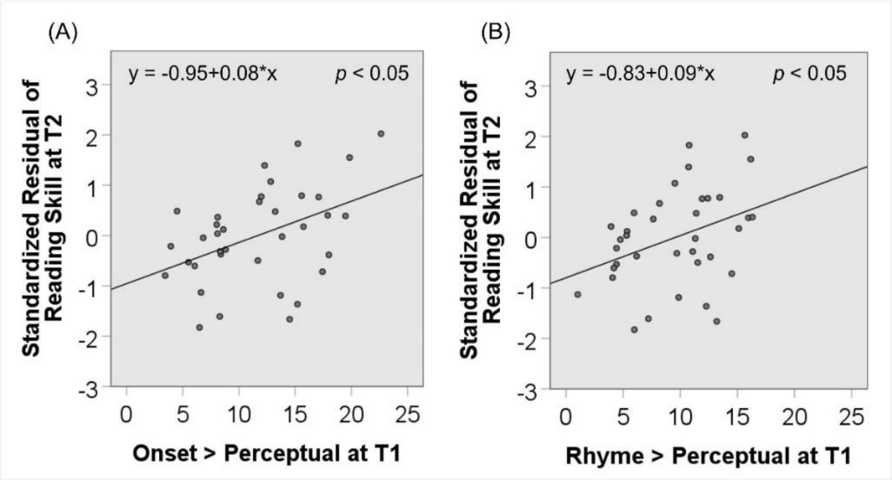
Younger cohort

The regression analysis that examined the scaffolding hypothesis showed that brain activation in STG for both phoneme (onset > perceptual, *p* = 0.015) and rhyme (rhyme > perceptual, *p* = 0.032) significantly predicted reading skill at T2 after controlling for the reading skill at T1 and nonverbal IQ (see Table 4).

Table 4. The result of the hierarchical regression analyses examining the scaffolding hypothesis using brain activation in the younger cohort.

		Dependent measure					
		Reading skill at T2					
	Predictor	B	R^2	ΔR^2	B	R^2	ΔR^2
Model 1	Nonverbal IQ	-.025			-.025		
	Reading skill at T1	.802 ***	.693		.802 ***	.628	
Model 2	Nonverbal IQ	-.051			-.018		
	Reading skill at T1	.858 ***			.843 ***		
	Onset>Perceptual in STG at T1	**.261***	**.833**	**.065**			
	Rhyme>Perceptual in STG at T1				**.232***	**.680**	**.052**

* *p* < .05, ** *p* < .01, *** *p* < .001 uncorrected.



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[5] For the sake of saving space, here I only display the significant findings. Full results can be found in Wang, Joanisse, & Booth, (2020) and Wang, Pines, Joanisse, & Booth, (2021) in NeuroImage. In the Wang et al., (2020) study, we controlled phonological memory tested by CTOPP-2 at T1. However, in later studies, we decided to take the phonological control variable out because it involved the process of phonological access, an important variable that we cared about in the brain and thus should be not controlled for. To be consistent with other studies, I re-analyzed the data on the young cohort from the Wang et al., (2020) study by taking out the phonological control variable. New results are displayed in Table 5 and Figure 8, which remained the same as ones in the published paper.

Figure 8. The scatterplots for the relation (A) between onset processing at T1 and standardized residual of reading skill at T2 and (B) between rhyme processing at T1 and standardized residual of reading skill at T2 in the younger cohort.

Figure 8 shows the scatterplots for the relation between onset and rhyme processing at T1 and the standardized residual of reading skill at T2 after controlling for non-verbal IQ and reading skill at T1. Figure 8A and 8B shows that the greater brain activation during phonological awareness task in the left STG was at T1, the more they gained their reading skill over time.

Older cohort

The regression analysis that examined the refinement hypothesis using brain activation showed that reading skill was related to onset > perceptual in the opercular part of IFG at T2 ($p = 0.024$) after the effects of brain activation and non-verbal IQ at T1 were accounted for. However, reading skill did not significantly predict rhyme > perceptual in the opercular part of IFG at T2 after the effects of brain activation and non-verbal IQ at T1 were accounted for (see Table 5). Figure 9A shows the scatterplots for the relation between reading skill at T1 and standardized residual of brain activation in the left IFG at T2 after controlling for nonverbal IQ and brain activation at T1. As is shown in the figure, the higher children's initial reading skills were, the lower activation in their left IFG for onset processing.

Table 5. The result of the hierarchical regression analyses examining the refinement hypothesis using brain activation in the older cohort.

		Dependent variables					
		Onset>Perceptual IFG at T2			Rhyme>Perceptual IFG at T2		
	Predictor	β	R^2	ΔR^2	β	R^2	ΔR^2
Model 1	Non-verbal IQ	-.173			-.073		
	Onset>Perceptual in IFG at T1	.275*	.119				
	Rhyme>Perceptual in IFG at T1				.212	.059	
Model 2	Non-verbal IQ	-.058			.029		
	Onset>Perceptual in IFG at T1	.295*					
	Rhyme>Perceptual in IFG at T1				.238		
	Reading skill at T1	**-.303***	**.198**	**.079**	-.256	.115	.056

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ uncorrected.

The regression analysis that examined the scaffolding hypothesis showed that functional connectivity of IFG with STG for rhyme processing at T1 predicted reading skill at T2 after controlling reading skill and non-verbal IQ at T1 ($p = 0.029$). However, functional connectivity of IFG with STG for onset processing at T1 did not predict reading skill at T2 after controlling reading skill and non-verbal IQ at T1 (see Table 6). Figure 9B shows the scatterplot for the relation between functional connectivity of IFG with STG for rhyme processing at T1 and the standardized residual of reading skill at T2 after controlling for nonverbal IQ and reading skill at T1. As is shown in the figure, the stronger the connectivity between IFG and STG for rhyme processing was, the more they gained their reading skill over time.

Table 6. The result of the hierarchical regression analyses examining the scaffolding hypothesis using brain connectivity in the older cohort.

		Dependent measure					
		Reading skill at T2					
	Predictor	β	R^2	Δ R^2	β	R^2	Δ R^2
Model 1	Non-verbal IQ	.002			.002		
	Reading skill at T1	.855 ***	.731		.855 ***	.731	
Model 2	Non-verbal IQ	.004			-.012		
	Reading skill at T1	.860 ***			.890 ***		
	IFG-STG connectivity for onset > perceptual at T1	.037	.732	.001			
	IFG-STG connectivity for rhyme > perceptual at T1				**.154***	**.754**	**.023**

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ uncorrected.

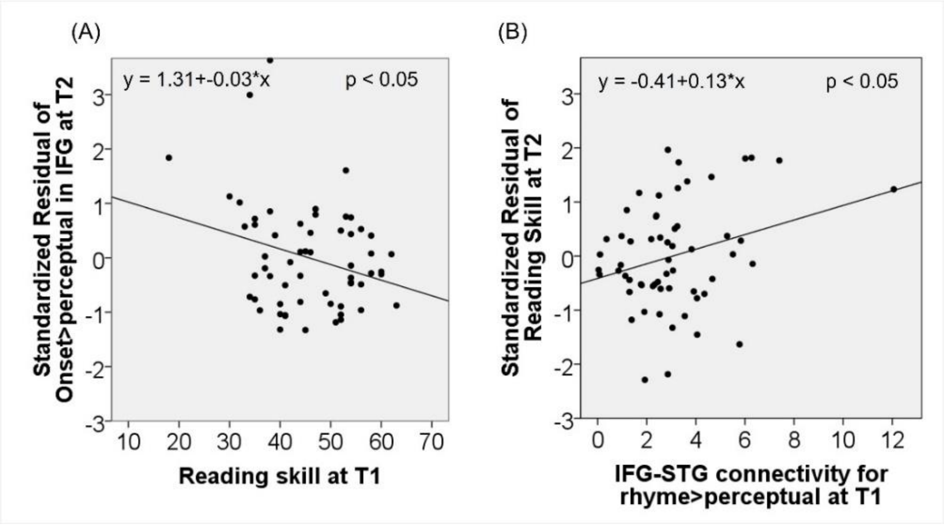

Figure 9. The scatterplots of (A) the relation between reading skill at T1 and the standardized residual of brain activation in IFG at T2 and (B) the relation between functional connectivity of IFG with STG at T1 and the standardized residual of reading skill at T2 in the older cohort.

Figure 10 shows the summary of the findings using univariate analyses in both young and older cohort. We only found a scaffolding that earlier brain activation for both small and large grain phonological representation in STG scaffolded later reading acquisition in young children (Wang et al., 2020). However, we found both scaffolding and sculpting effects in older children, where functional connectivity for rhymes between IFG and STG predicted later reading acquisition and earlier reading skill predicted later brain activation for phonemic access in IFG (Wang et al., 2021).

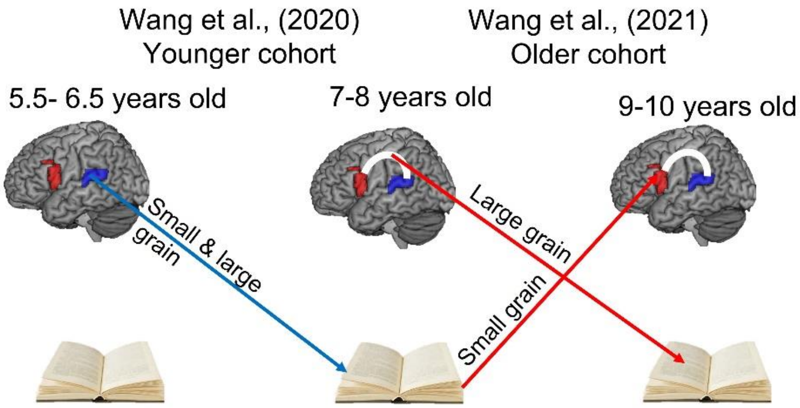

Figure 10. Results from univariate analyses on the relationship between reading skill and phonological processing during phonological awareness for both the younger and older cohort. These findings were published in Wang et al., (2020) and Wang et al., (2021).

3.2.3.2 Results from analysis 2 using multivariate analyses

Younger cohort

Figure 11 shows the decoding coefficients for onset versus unrelated processing and the decoding coefficients for rhyme versus unrelated processing at each time point. The regression analysis that examined the scaffolding hypothesis showed that only decoding coefficients of onset versus unrelated processing at T1 significantly predicted reading skill at T2 after controlling for reading skill and nonverbal IQ at T1 (p = 0.023). Decoding coefficients of rhyme versus unrelated processing at T1 did not predict reading skill at T2 (see Table 7). Figure 12A shows the scatterplot for the relation between decoding coefficients for onset versus unrelated processing at T1 and standardized residual of reading skill at T2 after controlling reading skill and nonverbal IQ at T1. As is shown in the figure, the higher the decoding coefficients for onset versus unrelated processing, the more children gained their reading skill over time.

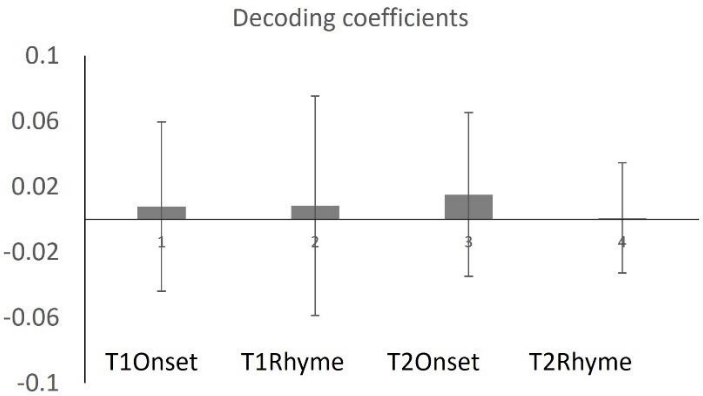

Figure 11. Decoding coefficients for Onset (i.e., onset versus unrelated processing) and decoding coefficients for Rhyme (i.e., rhyme versus unrelated processing) at time point 1 and 2 in the younger cohort. Error bar represents 1 standard deviation from the mean.

Table 7. The result of the hierarchical regression analyses examining the scaffolding hypothesis using multivoxel pattern analysis in the younger cohort.

			Dependent measure					
			T2 Reading skill					
	Step	Predictor	B	R^2	ΔR^2	B	R^2	ΔR^2
Model 1		T1 Nonverbal IQ	-.017			-.017		
	1	T1 Reading skill	.799***	.628		.799***	.628	
Model 2		T1 Nonverbal IQ	-.066			-.013		
	1	T1 Reading skill	.753***			.798***		
	2	T1 Decoding coefficients for Onset versus Unrelated in STG	**.241***	**.680**	**.051**			
	2	T1 Decoding coefficients for Rhyme versus Unrelated in STG				-.036	.630	.001

* $p < 0.05$, *** $p < 0.001$ uncorrected.

The regression analysis that examined the sculpting hypothesis showed that reading skill at T1 only predicted decoding coefficients of onset versus unrelated processing at T2 after controlling the decoding coefficients and nonverbal IQ at T1 ($p = 0.009$). Reading skill at T1 did not predict decoding coefficients of rhyme versus unrelated processing at T2 (see Table 8). Figure 12B shows the scatterplot for the relation between reading skill at T1 and standardized residual of decoding coefficients for onset versus unrelated processing at T2 after controlling for nonverbal IQ and decoding coefficients at T1. As is shown in the figure, the better the initial reading skill, the higher decoding coefficients for onset versus unrelated processing children at T2.

Table 8. The result of the hierarchical regression analyses examining the refinement hypothesis using multivoxel pattern analysis in the younger cohort.

		Dependent variables					
		Decoding coefficients of Onset versus Unrelated in STG at T2			Decoding coefficients of Rhyme versus Unrelated in STG at T2		
	Predictor	β	R^2	ΔR^2	β	R^2	ΔR^2
Model 1	Non-verbal IQ	-.112			.194		
	Decoding coefficients of Onset versus Unrelated in STG at T1	.218	.049				
	Decoding coefficients of Rhyme versus Unrelated in STG at T1				-.147	.057	
Model 2	Non-verbal IQ	-.281			.176		
	Decoding coefficients of Onset versus Unrelated in STG at T1	.076					
	Decoding coefficients of Rhyme versus Unrelated in STG at T1				-.146		
	Reading skill at T1	**.493****	**.232**	**.183**	.043	.059	.002

** $p < 0.01$ uncorrected.

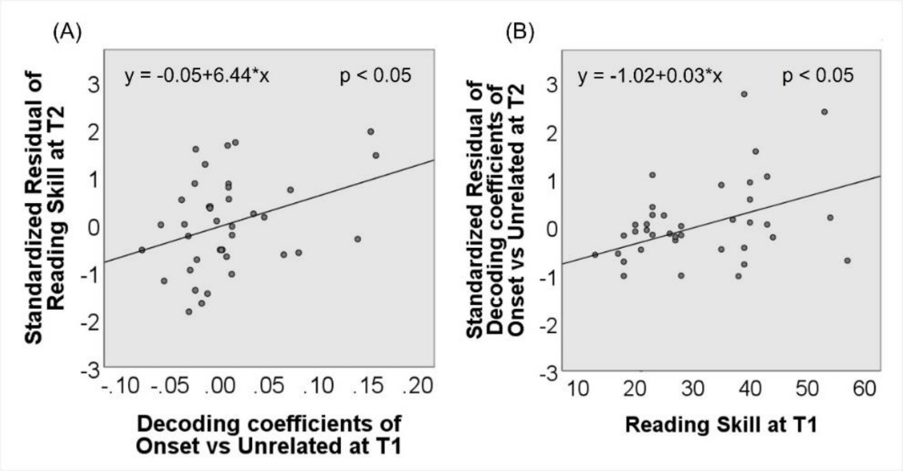

Figure 12. The scatterplots for (A) the relation between decoding coefficients of onset versus unrelated processing at T1 and standardized residual of reading skill at T2 and (B) the relation between reading skill at T1 and standardized residual of decoding coefficients of onset versus unrelated processing at T2.

Older cohort

Figure 13 shows the decoding coefficients for onset versus unrelated processing and the decoding coefficients for rhyme versus unrelated processing at each time point. The regression analysis that examined the scaffolding hypothesis showed that decoding coefficients of onset versus unrelated processing at T1 did not predict reading skill at T2 after controlling for reading skill and nonverbal IQ at T1. In addition, decoding coefficients of rhyme versus unrelated processing at T1 did not predict reading skill at T2 (see Table 9).

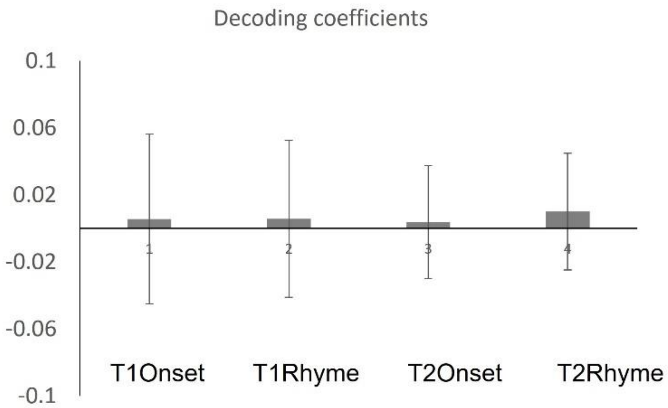

Figure 13. Decoding coefficients for Onset (i.e., onset versus unrelated processing) and decoding coefficients for Rhyme (i.e., rhyme versus unrelated processing) at time point 1 and 2 in the older cohort. Error bar represents 1 standard deviation from the mean.

Table 9. The result of the hierarchical regression analyses examining the scaffolding hypothesis using multivoxel pattern analysis in the older cohort.

			Dependent measure					
			T2 Reading skill					
	Step	Predictor	B	R2	Δ R2	B	R2	Δ R2
Model 1		T1 Nonverbal IQ	0			0		
	1	T1 Reading skill	.859***	.738		.859***	.738	
Model 2		T1 Nonverbal IQ	0			-.001		
	1	T1 Reading skill	.861***			.860***		
	2	T1 Decoding coefficients for Onset versus Unrelated in STG	-.011	.738	0			
	2	T1 Decoding coefficients for Rhyme versus Unrelated in STG				.005	.738	0

*** *p* < 0.001 uncorrected.

The regression analysis that examined the sculpting hypothesis showed that reading skill at T1 did not predict decoding coefficients of onset versus unrelated processing at T2 after controlling the decoding coefficients and nonverbal IQ at T1. In addition, reading skill at T1 did not predict decoding coefficients of rhyme versus unrelated processing at T2 (see Table 10).

Table 10. The result of the hierarchical regression analyses examining the refinement hypothesis using multivoxel pattern analysis in the older cohort.

		Dependent variables					
		Decoding coefficients of Onset versus Unrelated in STG at T2			Decoding coefficients of Rhyme versus Unrelated in STG at T2		
	Predictor	β	R^2	ΔR^2	β	R^2	ΔR^2
Model 1	Non-verbal IQ	-.014			-.057		
	Decoding coefficients of Onset versus Unrelated in STG at T1	-.090	.009				
	Decoding coefficients of Rhyme versus Unrelated in STG at T1				-.070	.009	
Model 2	Non-verbal IQ	.027			-.112		
	Decoding coefficients of Onset versus Unrelated in STG at T1	-.060					
	Decoding coefficients of Rhyme versus Unrelated in STG at T1				-.061		
	Reading skill at T1	-.134	.024	.015	.149	.028	.019

Figure 14 shows the summary of the findings using MVPA in both young and older cohort. We found both scaffolding and sculpting effects in young children, where the precision of small grain phonological representations in STG scaffolded later reading acquisition and earlier reading sculpted later representational precision of small grain phonemes in STG. We did not find any scaffolding or sculpting effects in terms of phonological representations in STG in older children.

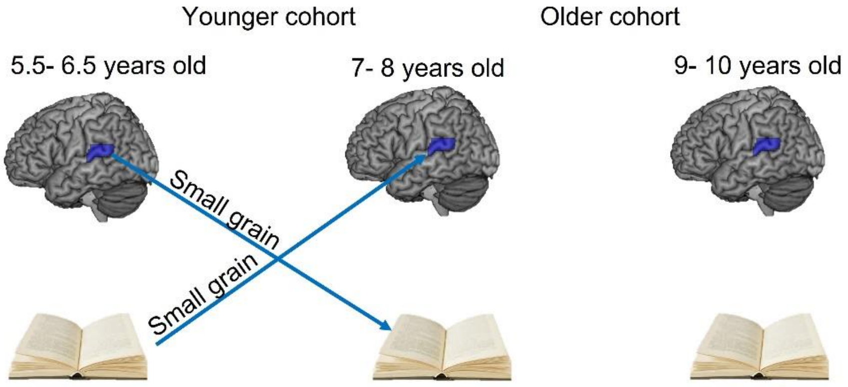

Figure 14. Results from MVPA on the relationship between reading skill and phonological processing during

phonological awareness for both the younger and older cohort.

3.2.4 Discussion

Study 3 & 4 aimed to examine the longitudinal relation between reading skill and phonological processing. Using univariate analyses, my previously published studies found that in the younger cohort, brain activation in the left STG for both onset and rhyme processing scaffolded later reading skill. In the older cohort, both scaffolding and sculpting effects were observed. Functional connectivity between the left IFG and STG for rhyme processing scaffolded later reading skill, whereas earlier reading skill sculpted later brain activation in IFG for onset processing. These findings are generally consistent with our hypothesis that smaller grain sizes play a role earlier in reading than larger grain sizes. In addition, they align with the neurocognitive model of language (Skeide, et al., 2016) that the temporal lobe plays a role earlier than the frontal lobe. Detailed discussion of the univariate findings can be found in Wang, Joanisse, & Booth (2020) and Wang, Pines, Joaniesse, & Booth (2021).

Univariate analyses treat each voxel as an independent piece of data, using statistics to determine whether that voxel responds more in some experimental conditions than in others. Multivariate analyses, however, take into consideration covariance among voxels that may carry weak but informative information, making it a sensitive tool to detect effects even if the average level of activity does not differ between conditions (Tong & Pratte, 2012). Therefore, we used MVPA as an alternative approach to index the quality of phonological representations stored in STG and investigated its longitudinal relation with reading skill. We found that both scaffolding and sculpting effects occurred in young children. Specifically, for onset versus unrelated processing, earlier decoding coefficients significantly predicted later reading skill and earlier reading skill significantly predicted later decoding coefficients. These effects were specific to the small grain phonological representations as there were no effects using decoding coefficients of rhyme versus unrelated processing. In addition, no scaffolding or sculpting effects for either small or large grain phonological representations in STG were observed in older children. These findings are consistent with our hypotheses that both scaffolding and sculpting effects would occur early in development, and that reading would be associated to a larger degree with small grain phonological representations in STG.

The observation of a scaffolding effect for small grain sizes in young children using MVPA is consistent with our finding using univariate analyses. This is as expected because according to the theories of reading development (Frith, 1985, Ehri, 2020), young children primarily rely on small grain letter-to-phoneme mapping during visual word decoding, and better quality of small grain phonemic representations facilitates the mapping between distinct visual letters and phonemes. However, different from the univariate results which showed that brain activation for rhyme processing also scaffolded later reading skill in young children, the current MVPA results did not show such an effect. This discrepancy may be because the two analytical approaches extract difference sources of variance (Davis, et al., 2014). Voxel-wise univariate analyses are more sensitive to variance in subject-level mean activation. MVPA, however, is more sensitive to variance in spatial patterns across voxels and thus is potentially a more direct measure for the precision of stimulus representation (Davis, & Poldrack, 2013). Our univariate findings, which showed both grain sizes predicted reading skill, suggests that greater engagement of phonological representations during auditory word processing is related to greater gains in reading skill. However, our MVPA findings suggest that only the representational precision of small grain sizes scaffolds later reading skill in young children.

In addition to a scaffolding effect in young children, we found that earlier reading skill predicted later representational precision of small grain sizes, supporting a sculpting effect. This is consistent with the connectionist model of reading (Harm & Seidenberg, 1999), which shows a reciprocal relation between reading acquisition and the quality of phonological representations. Our MVPA results further suggest that this sculpting effect of earlier reading on later phonological representations only occurs for small grain sizes because there were no sculpting effects on decoding coefficients for rhyme versus unrelated processing. This sculpting effect on small grain phonemes aligns with the developmental theory of phonological awareness (Anthony, & Francis, 2005), which suggests that phonological awareness develops from large to small grain sizes, becoming finer grained as children grow older. Although we observed a sculpting effect using MVPA, no sculpting effects were found using univariate analyses in our previous study using univariate analyses. The difference between univariate and multivariate results may be because 7- to 8-year-old children already grasped phonemic awareness, and the ease of performing such a task reduced brain engagement in STG, resulting in a lack of a sculpting effect. As mentioned, MVPA is not sensitive to subject-level mean activation (Davis, et al., 2015), so the decoding coefficients in STG were more likely to capture the precision of phonological representations. This increased sensitivity of MVPA may have allowed the discovery of the sculpting effect of earlier reading skill on later phonemic representations, which supports the connectionist model.

Unlike young children who showed both scaffolding and sculpting effects, older children did not show any longitudinal effects using MVPA for phonological representations in STG. This lack of findings is consistent with our previous study on older children using univariate analyses. However, using univariate analyses, we did find that phonological access in IFG played a role in both scaffolding and sculpting processes in older children. Together with the findings from young children which showed effects only in STG but not IFG, we suggest a developmental transition of reading from being associated with phonological representation in STG to being more related to phonological access in IFG. This developmental transition is consistent with a neurocognitive model of language development (Skeide, & Friederici, 2016), which argues that processes in the temporal lobe matures earlier than those in the frontal lobe. In addition, our findings are consistent with previous neuroimaging research, which showed that brain activation in the left STG during phonological tasks was correlated with reading skill in young children (Raschle et al., 2012; Luniewska et al., 2019; Debska et al., 2016; Chyl et al., 2018; Vandermosten et al., 2019), whereas brain activation in the left IFG during phonological tasks was associated with reading skill in older elementary children or adults (Corina et al., 2001; Heim et al., 2010; Cao et al., 2017; Boets et al., 2010).

In summary, study 3 & 4 examined the longitudinal relation between reading and two phonological processes during an auditory phonological awareness task, using both univariate and multivariate analyses. We found scaffolding and sculpting processes unfold differently in developing children. Specifically, phonological representations in STG played an earlier role than phonological access in IFG in the reciprocal relation between reading skill and phonological processing. Secondly, small grain sizes scaffolded reading earlier than larger grain sizes because reading is expected to progress from small to large grain size mapping. Finally, earlier reading skill always sculpted later phonological representations at small grain sizes because phonological awareness is expected develop from large to small grain sizes.

4. General discussion

Overall, my dissertation studies examined the longitudinal relation between reading skill and the neural basis of phonological awareness in developing children. Through examining the scaffolding and sculpting processes and how they unfolded during development, my dissertation contributes to reading theories in the following three aspects.

Firstly, my dissertation studies systematically examined the role of grain size in reading development. I found that small grain onset processing scaffolded reading skill earlier than large grain rhyme processing in developing children. Although the connectionist model has indicated that small grain size mapping requires less computation and thus is acquired faster than larger grain size mapping, it was only tested to simulate the different learning rates of regular versus irregular words (Seidenberg, 1993). Decoding regular words tends to rely on small grain letter-to-phoneme mapping, whereas decoding irregular words tends to rely on larger grain orthography-to-phonology mapping. Previous behavioral studies have suggested that the measures of phonemic awareness are stronger predictors of later reading skill than the measures of rhyme awareness in young children (e.g., Muter, et al., 1998; Hulme et al., 2002; Muter et al., 2004; Castles & Coltheart, 2004). However, the grain size effects of phonological awareness on reading acquisition in older children remained unclear. By examining both designing small (i.e., onset) and large (i.e., rhyme) grain conditions in a phonological awareness task and utilizing fMRI, my dissertation studies suggest that reading also follows a developmental transition from relying on small grain letter-to-phoneme mapping to relying on larger grain orthography-to-phonology mapping, providing additional constraints to the connectionist model.

Secondly, my dissertation provides first neural evidence on the role of automatic orthographic activation during auditory processing in reading acquisition. Although the connectionist model suggests that a feedback mapping from phonology to orthography is influenced by reading acquisition, and that this feedback mapping facilitates word recognition, previous examinations of this model only focused on how the activation of orthographic representations through visual input is related to reading acquisition (e.g., Seidenberg, 1992; Cunningham et al., 2010; Centanni, et al., 2019). Previous neuroimaging research has examined the concurrent relation between reading skill and automatic orthographic activation in vOT during auditory processing (Raschle, et al., 2012; Wang, Joanisse, & Booth, 2018; Debska et al., 2016; Wang et al., 2021; Derosches et al., 2010; Debska et al., 2019). However, no studies have examined the directionality of the relation. By employing a longitudinal design and fMRI, my dissertation studies addressed the literature gap and found that the feedback mapping from phonology to orthography as indicated by functional connectivity between STG and vOT during auditory processing was a result of learning to read in young children. In addition, automatic orthographic activation in vOT in young children served as a scaffold for later reading acquisition. These findings provide direct neural evidence supporting the feedback mapping hypotheses from the connectionist model.

Finally, my dissertation suggests that two phonological processes should be incorporated into reading models. The current connectionist model only contains one phonological representation system to explain the process of reading development. Although previous neural research has suggested that phonological representations in the left STG and phonological access in the left IFG are associated with reading skill differently in development (Raschle et al., 2012; Luniewska et al., 2019; Debska et al., 2016; Chyl et al., 2018; Vandermosten et al., 2019; Corina et al., 2001; Heim et al., 2010; Cao et al., 2017), these studies have only examined concurrent correlations, and therefore unable to infer the directionality of the relation. My dissertation studies addressed this issue and found that early in development, only phonological representation in STG scaffolded and was sculpted by reading skill. Later on, phonological access in IFG started to play a role. These findings suggest a necessity of adding a control system to the connectionist model so that it can account for the role of phonological access, to provide a better and more neurally plausible account for reading development.

5. Future directions

For future steps, there are three new directions that I want to pursue to develop my framework for understanding the reciprocal relation between language skills and reading development.

The first direction that I am interested in is to examine the bidirectional relation between automatic orthographic activation and phonological representations during phonological awareness tasks. How learning to read changes the nature of language processing is debated in the literature (Chao, Chen, Zevin, & Lee, 2021). The phonological restructuring view argues that learning to read refines the phonological representations during spoken language processing (e.g., Taft & Hambly, 1985; Muneaux & Ziegler, 2004). However, the orthographic co-activation view suggests that learning to read leads to an online co-activation of orthographic representations (e.g., Dehaene & Cohen, 2007). My dissertation studies, which independently examined how automatic orthographic activation and phonological processing interacted with reading acquisition longitudinally, showed evidence supporting both views. However, a factor that is ignored by the two views and my dissertation studies is the relation between automatic orthographic and phonological representations. These processes likely influence each other over development. For example, my previous studies observed that beginning readers relied on letter representations in the posterior vOT for phonemic processing, but older children relied on their refined phonological representations in STG for phonemic processing. In addition, older children relied on rime representations in the anterior vOT for rhyme processing as a function of their reading skill (Wang, Joanisse, & Booth, 2018; Wang, Joanisse, & Booth, 2021). Although our previous cross-sectional studies observed a developmental difference in the reliance on automatic orthographic activation in vOT and phonological representations in STG during phonological tasks, we do not know how these two representations interact with each other to achieve this developmental change. In addition, we do not know how grain sizes and age might play a role in this interaction. Addressing these questions is important because it can shed light on previous debates between the phonological restructuring and the orthographic co-activation views.

In terms of the directional relation between automatic orthographic activation in vOT and phonological representation in STG, I have the following hypotheses. For small grain size phonemic processing, because greater utilization of mapping to letter representations will help young children better recognize the acoustically inseparable phonemes in spoken words, I expect that in young children, automatic letter representations in the posterior vOT would refine later phonemic representations in STG. However, as children’s phonemic representations become more fine-tuned (Anthony, & Francis, 2005) and their reading progresses to larger grain orthography-to-phonology mapping (Frith, 1985), directly relying on phonemic representations to perform auditory tasks becomes more efficient than relying on their letter representations. Thus, I expect that in older children, better phonemic representations in STG would reduce the engagement of letter representations in the posterior vOT. For large grain rhyme processing, because rhyme awareness is well developed early in life (Anthony, 2005) and reading progresses to larger grain orthography-to-phonology mapping (Frith, 1985), I would expect that in both young and older children, better rhyme representations in STG would predict greater later rime representations in the anterior vOT. However, because rhyme in spoken words is easy to detect auditorily without relying on their spellings, rime representations in the anterior vOT should not affect later rhyme representations in STG. All these hypotheses can be examined using the existing dataset from my dissertation.

My second future research interest is to examine the bidirectional relationship between semantic processing and reading skill in developing children. My dissertation only focused on orthography and phonology in the connectionist model of reading. The bidirectional relation between semantic processing and word reading remains unclear. Previous longitudinal behavioral research has consistently shown that vocabulary is a significant early predictor for reading comprehension. However, its relationship with word reading skills is inconsistent (e.g., Roth, Speece, & Cooper, 2002; Verhoeven, Leeuwe, & Vermeer, 2011). Although vocabulary is generally treated as a proxy for semantic processing skill, Quellette (2006) pointed out that the breadth and depth of vocabulary are different. The former reflects the number of lexical items or phonological word forms, whereas the latter is associated with the quality of semantic representations. By separating these components, Quellette and Beers (2010) found that although the depth of vocabulary knowledge was only predictive of reading comprehension but not word reading skill in 6th graders, it predicted irregular word reading skill in 1st graders. This finding is consistent with the connectionist model, suggesting that when orthography-to-phonology mapping is not sufficient for decoding visual words, the quality of semantic representation helps with word recognition. However, this study is not a longitudinal design, making it difficult to draw conclusions about directionality. Some behavioral studies used a longitudinal design and found an early scaffolding and a later sculpting effect between word reading skill and vocabulary in elementary schoolers (e.g., Verhoeven, et al., 2011). However, it is not clear whether these effects were due to semantic skills because they only measured vocabulary breadth and did not control for phonological skills.

Neuroimaging provides an alternative measure for semantic processing by measuring brain activities in semantic regions such as the left ventral IFG and MTG (e.g., Friederici & Gierhan, 2013; Binder et al., 2009). Some previous studies examined brain activation differences in children with and without reading difficulties during auditory semantic judgment tasks. They found that, as compared to typically developing children, children with reading difficulties showed either weaker activation or less sensitivity to association strength in semantic brain areas such as the left ventral IFG and MTG (e.g., Booth, et al., 2007; Landi, et al., 2010). However, little research has directly correlated word reading skill with semantic processing during auditory tasks, let alone testing the directionality of their relation. To fill this literature gap, I aim to examine the longitudinal relation between the relation between reading skill and semantic processing during auditory tasks. This line of research can be conducted using the existing dataset that we shared on OpenNeuro.org (Wang et al., 2022), which included a semantic judgement fMRI task using auditory word stimuli. Because children were asked to judge the semantic associations between two auditory words with both high and low associated words, this task taps into the quality of semantic representations rather than the breath.

Given that the connectionist model (Seidenberg, 1992) suggests a reciprocal relation between semantic representations and reading acquisition, I would expect that both scaffolding and sculpting effects will occur, but those effects will appear at different ages. Specifically, semantic skill will scaffold later reading skill in young but not older children, because when young children's orthography-to-phonological mapping is not well established, a good representation of semantics can help them decode visual words. In addition, reading skill will refine later semantic skill in older but not young children. This is because older children have higher reading skills, which allow them to both learn new vocabulary and deepen their understanding of known words in context through reading, resulting in an improvement of their semantic skills.

Finally, I am interested in exploring how early home literacy environment (HLE) influence later pre-reading language processing in young children. The emergence of this interest is because we found an early automatic activation in the anterior vOT for rhyme in 6-year-old children that scaffolded their subsequent reading skill. Six years old is too young to establish large grain rhyme-to-rime mapping. Thus, we speculated that it could be early literacy experience, such as shared book reading, that promoted a holistic visual-sound mapping in children's brain even before they could decode words. A previous study suggested that the left vOT is functionally connected with language areas in the infant brain (Li, et al., 2020). Thus, it is also possible that early brain structure and functional connectivity serve as a foundation for re-shaping later language processing. In the literature, only a few neuroimaging studies examined the role of HLE on pre-reading language processing in the brain. They showed that better HLE was associated with greater activation in reading-related areas during phonological or story-listening tasks (e.g., Powers, et al., 2016; Hutton, et al., 2021). However, these studies only concurrently correlated HLE with brain activity, making it difficult to draw conclusions on directionality. In addition, they did not consider the joint influence of early brain structure or functional network on later language processing. Therefore, in the future, by using a longitudinal design and incorporating early brain measures, I would like to answer if HLE affects pre-reading language processing beyond early brain characteristics and how HLE and early brain features interact with each other to impact pre-reading language skills. Addressing these questions will inform early intervention practice on children's reading-readiness. Because our existing dataset shared on Openneuro.org (Wang et al., 2022) also includes a measure on HLE at ses-7 and ses-9, some of these questions can be firstly tested in older children.

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