Neural and Behavioral Foundations of Emerging Literacy

by

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Dedication

To my matriarchs.

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Abstract

Learning to read transforms the mind and brain as children learn to recognize language in its printed form. This dissertation asks, *how does spoken language processing support reading development?* This inquiry is centered around theoretical frameworks that suggest that skilled reading depends on closely connected representations of sound, print, and meaning. In three separate studies, I explore the neurocognitive basis of reading development and its relation to spoken language processing, with a particular focus on children's sensitivity to units of meaning in language. First, I examine the interrelation between spoken and written word processing in the brain of 133 5–6-year-old kindergarteners, 68 of whom participated in functional Magnetic Resonance Imaging (fMRI). This first study reveals that children's emerging neural architecture for a shared print-speech network is best explained by their spoken language proficiency, and that the extent of this shared network in kindergarten predicts reading skill one year later. Next, I examine the role of *morphological awareness*, or children's sensitivity to units of meaning, in a large, linguistically diverse sample of 340 monolingual and bilingual children, ages 5–9. Using a novel behavioral measure of morphological awareness, as well as standardized behavioral language and literacy assessments, I reveal that morphological awareness makes a robust independent contribution to early literacy skill, and that this association varies as a function of children's bilingual language backgrounds. Finally, I use functional Near Infrared Spectroscopy (fNIRS) neuroimaging to investigate the brain basis of morphological awareness and its relation to successful reading comprehension in 97 6–11-year-olds, 25% of whom were reading impaired. I find that during a morphological awareness task, better readers demonstrate increased

engagement of brain regions associated with integrating units of sound, meaning, and print, while impaired readers fail to show this association. Taken together, these dissertation findings suggest that children's language ability is a core mechanism guiding the neural plasticity for learning to read, and inform theoretical perspectives on the role of morphology in the reading development of diverse learners.

CHAPTER I. Introduction

Reading, at its core, is the act of recognizing language in print. To understand reading, one must therefore understand its relationship to concurrent language development. This dissertation examines the relation between language and literacy acquisition over the course of elementary school to attain a more complete understanding of child language development in both its auditory and visual forms. The guiding question I address in my dissertation is: **How does spoken language processing support reading development?**

Learning to read builds upon a child's existing linguistic knowledge and mechanisms for language processing. It is well established that children's spoken language skills precede and predict reading outcomes long before children learn to read. For instance, sensitivity to word sounds in preschool (e.g., rhyme and alliteration) predicts reading and spelling three years later (Bradley & Bryant, 1985), and vocabulary prior to age two significantly predicts word reading accuracy and reading comprehension five years later (Duff et al., 2015). By age 2½, children who later exhibit reading disorders demonstrate poorer spoken language ability than typical readers (Scarborough, 1990). Remarkably, a recent longitudinal study revealed that children's spoken language proficiency before the onset of formal schooling – as measured in terms of phonological, morphological and semantic ability – was directly associated with children's reading comprehension in the first year of high school (Lyster et al., 2020).

In addition to this strong link between language and literacy that we may observe in behavior, language and literacy are also closely connected at the neural level. The brain basis of spoken language processing is also a predictor of future reading ability (e.g., Debska et al., 2016). For instance, neural responses to speech sounds in infancy can further predict children's pre-reading skills prior to the start of school (Guttorm et al., 2010). Indeed, neurocognitive evidence suggests that learning to read builds upon, or "recycles," an individuals' neural architecture for spoken language (Dehaene, 2004; Dehaene & Cohen, 2007). Furthermore, this connection between language and literacy is reciprocal. Learning to read changes neural systems for spoken language processing, enhancing activation in the temporal cortex in response to speech (Dehaene et al., 2015), and increasing the connectivity between visual and auditory processing regions (López-Barroso et al., 2020).

A truly comprehensive model of word reading acquisition will be supported by both behavioral and neuroscientific evidence from developmental samples. To this end, my dissertation uses a complementary brain-behavior approach to identify cognitive processes that underlie word reading. I begin by examining language and literacy at the level of whole word processing (Study 1), and progress to a more granular examination of the sub-lexical processes underlying literacy, both behaviorally (Study 2) and in the brain (Study 3). The behavioral data collected provides valuable insight into the relation between language skills and reading development at a broad level. Complementary neuroimaging findings in Studies 1 and 3 shed light on more granular neurocognitive mechanisms underlying language processing, and the means by which they support word reading.

Learning to Read Words

The goal of reading is to access mental representations of language. First, children must recognize that language can be represented by visual forms; then, they begin to connect small units of language to units of print. This is a lengthy, multistage process that requires years of effort and instruction. In her **developmental phase model**, Linnea Ehri (1995) describes how single word reading skill develops in readers of alphabetic languages such as English. Initially, a child develops logographic skills, or the ability to recognize familiar words in their entirety. In this pre-alphabetic phase, a child may recognize the word "STOP" as a whole unit that appears on road signs. Children then acquire alphabetic skills and learn to connect language sounds (*phonemes*) with individual letters (*graphemes*). At this stage, a child may recognize the composite letters that make up the word STOP, and associate each letter with an individual sound. Beginning readers often need to sound out printed words by articulating each letter to understand the word's meaning ("s-t-o-p"). Children's phonological awareness – their sensitivity to, or ability to manipulate small units of sound – is a powerful predictor of early reading skill across languages (McBride-Chang & Kail, 2002), and phonics instruction in school is known to support literacy acquisition (Ehri et al., 2001).

With time and practice, readers eventually learn to recognize larger units of print, or clusters of letters. Ideally, these clusters correspond to units of meaning, or *morphemes* (Ehri, 2013; Frith, 1985). For instance, a proficient reader might recognize the word "un-stopp-able" as a composite of morpho-syllabic units. This process becomes increasingly efficient, and over time, children become able to automatically link whole word forms with their phonological and conceptual representations (Ehri, 2014). Some evidence has suggested that children's morphological awareness, or sensitivity to linguistic units of meaning, plays an increasingly important role in reading as children progress through elementary and middle school (e.g., Singson et al., 2000).

Neurocognitive Theories of Word Reading

Consistent with Ehri's (1995) developmental theoretical perspective, neuroimaging studies of single word reading reveal a transition from more *effortful* processing that relies on phonological and articulatory systems, to more *automated* processing that directly connects visual and conceptual representations (Turkeltaub et al., 2003; Zhou et al., 2021). These neurocognitive systems are detailed below.

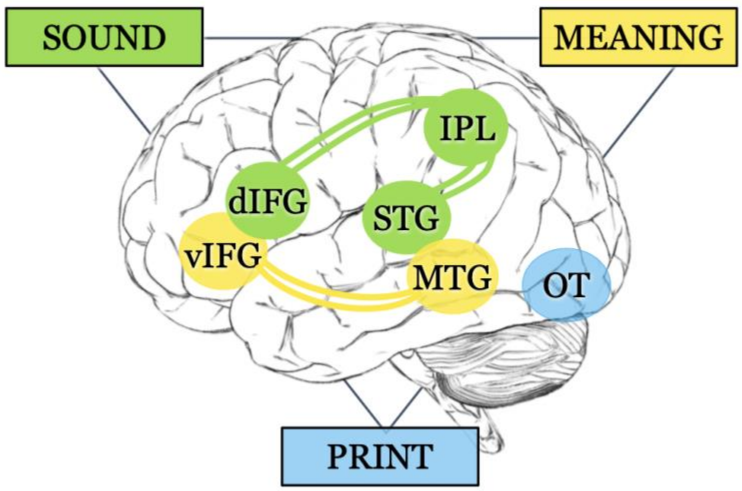


Figure I.1 *The neurocognitive view of literacy.*

Note. The dorsal route is represented in green, and the ventral route is represented in yellow.

During single word reading, beginning English readers recruit a *dorsal* or *phonological reading network* that connects canonical language regions with the premotor and primary visual cortex. Early readers rely on regions associated with phonological processing such as the inferior frontal gyrus (IFG), which includes Broca's area, and the superior temporal gyrus (STG), which includes Wernicke's area. Connecting these two regions to each other is the arcuate fasciculus, a large bundle of white matter fibers. The arcuate also connects Broca's and Wernicke's regions to the inferior parietal lobule (IPL), which is thought to integrate representations of sound, meaning, and print. This phonological route to reading is critical for young readers who rely on effortful processing necessary to integrate representations of print, sound, articulation, and meaning. Recent work has demonstrated that compared to fluent adult readers, children demonstrate greater functional connectivity between the left IFG and STG, as well as greater connectivity between bilateral auditory processing regions when reading text (Zhou et al., 2021). These findings point to the greater reliance on phonological processes during the earlier stages of reading development.

As sound-to-print connections become automatic, readers can devote fewer resources to phonological processing. This is due in part to the increased efficiency of the phonological network. Readers increasingly rely on a *ventral* or *semantic reading network* that efficiently connects the visual word form to representations of print and meaning. Reading proficiency is correlated with decreased activity in the left IFG, and increased activity in the left middle temporal gyrus (MTG), a region associated with semantic retrieval (Turkeltaub et al., 2003). Reading proficiency is also associated with increasing specificity in the occipitotemporal cortex (OT) in response to printed words. Greater activation in one specific region of the OT, known as the Visual Word Form Area, is associated with increased reading fluency, and is thought to support rapid word recognition and connection to lexical information (Dehaene, Cohen, Morais, & Kolinsky, 2015). In other words, proficient readers can bypass effortful auditory recoding and phonological processing and directly derive the meaning of a word from its orthographic form. In support of this developmental perspective, Zhou and colleagues (2021) found that compared to children, adult readers demonstrated greater functional connectivity between left frontal regions, left MTG and left angular gyrus, as well as between left lateralized occipitotemporal regions. This greater reliance on regions related to semantics and print processing in adults demonstrates the increased automaticity of meaning-to-print associations.

Of course, proficient readers do not rely solely on the ventral or semantic reading network. Instead, they integrate the dorsal and ventral reading networks in parallel, with some variation depending on the psycholinguistic features of the task at hand. For example, adults show stronger activation in the left IFG region when reading low frequency words (e.g., *anointed*), or pseudowords (e.g., *blicket*) that require careful sound-to-print mapping. In contrast, they demonstrate greater activation in the left MTG and occipito-temporal regions when reading high frequency words, which is thought to reflect the automatized connection between word meanings and orthographic representations (Fiebach, Friederici, & Cramon, 2002). Proficient word reading can thus rely on mechanisms for phonological decoding, as well as mechanisms for rapid meaning recognition.

Psycholinguistic Theories of Word Reading

This dissertation is largely guided by the **Lexical Quality Hypothesis** (LQH; Perfetti & Hart, 2002; Perfetti, 2007), which situates word knowledge at the center of fluent reading. The Lexical Quality Hypothesis suggests that a child's knowledge of a word is comprised of three interconnected constituents: sound (*phonology*), meaning (*semantics*), and print (*orthography*). Successful word reading depends on closely connected representations of sound, meaning, and print. In other words, for a child to successfully identify a word, they must look at the printed word form and efficiently connect that printed form to the correct pronunciation and word meaning. For a beginning or struggling reader, these connections may not be strong enough for fluent word recognition. In the absence of strong sound-to-print connections, a reader may struggle to sound out or correctly pronounce the word they see. In the absence of strong meaning-to-print or meaning-to-sound connections, a reader may be able to pronounce the word correctly but may not understand the meaning of the word. Experience with a given word, such as seeing it in print, learning the definition, or hearing it used in various contexts, reinforces and strengthens the connections between these constituents (Perfetti & Hart, 2002).

Cross-Linguistic Variation in Reading Development

Importantly, the associations between sound, meaning and print vary across languages and orthographies. For instance, in alphabetic languages such as Finnish, Spanish, or Korean, units of print correspond to individual sounds; in Japanese Hiragana orthography, units of print map on to syllables. In Chinese, written characters correspond to units of meaning, and provide minimal information about the composite sounds of a given word.

This cross-linguistic variation in how orthographies map onto spoken language often corresponds to language-specific differences in word structure (Frost, 2012; Seidenberg, 2012). In Semitic languages, for instance, root morphemes consist of three consonants, such as the root אכל (A.K.L.) which conveys the notion of food or eating. This root morpheme can be combined with patterns of vowels (word pattern morphemes) to modify the meaning. For instance, different vowel patterns, denoted here in diacritics, modify the root A.K.L. to form the words אֹכֶל (food), אֲכִילָה (eating), and מַאֲכָל (dish). Because word pattern morphemes are highly constrained and predictable, proficient Hebrew readers can access word meaning with or without the additional phonemic information provided by diacritic vowels (Frost, 2012).

Unlike Semitic languages, Indo-European languages require an orthography that presents detailed phonemic information. Consider, for example, the ambiguity in the three consonants P.N.T., which in English, could denote *pint*, *paint*, *pointy,* or *pinot.* Furthermore, root morphemes in Indo-European languages are often long and more phonologically complex.

In Spanish, for instance, words are typically polysyllabic, and can include multiple morphosyntactic markers of tense or gender that are as small as a single phoneme. The Roman alphabet is thus well-suited to the linguistic structure of Spanish, as orthographic units correspond to individual sounds, providing a reader with detailed information about pronunciation.

In contrast, orthographic units in Chinese typically correspond to morphemes. Most Chinese words are lexical compounds, comprised of two to three monosyllabic morphemes (akin to "birth-day" or "snow-man"). These morpho-syllables are often homophones, which means that the same combination of sounds may be associated with many different meanings. Like the English homophones "meet" and "meat," Chinese is abundant with homophone pairs like 钱 (qián) meaning "money" and 前 (qián) meaning "before." Chinese orthography thus prioritizes conveying information about meaning, rather than information about sound.

These structural differences across languages, and the ways in which language maps onto orthography, affect the process of learning to read. **Psycholinguistic Grain Size Theory** (Ziegler & Goswami, 2005) suggests that orthographies vary in the size of the linguistic unit that is key for reading success. Readers of alphabetic languages with consistent sound-to-letter mappings, such as Finnish or Spanish, can effectively read words at a small grain size by mapping individual sounds onto letters.

In contrast, English readers are thought to parse text at a larger grain size. In English, one letter may have multiple sounds (such as the *c* in *click, check* or *circle*), while one phoneme might be spelled multiple ways (such as the */k/* sound in *castle, kitten, locker,* and *echo*). Moreover, common English vocabulary often has a complex phonological structure and irregular spelling, such as in *people, could,* or *through.* As a result, English word reading development follows a somewhat different developmental trajectory than more consistent alphabetic languages. In contrast to Finnish, Spanish, and Dutch readers who reach near-ceiling word reading accuracy after one year of formal schooling, English-speaking children typically take until the end of 4th grade to achieve similar accuracy (Wimmer & Aro, 2003).

In addition to influencing the length of time it takes children to read high word reading accuracy, the varying emphasis on sound-to-print and meaning-to-print associations across languages influence children's relative reliance on various metalinguistic skills (Katz & Frost, 1992). For instance, in a cross-linguistic comparison of second-grade readers, path analyses revealed that phonological awareness made the greatest contribution to word reading in English, an alphabetic language. In contrast, morphological awareness and vocabulary knowledge significantly predicted word reading in Chinese, while phonological awareness made a much smaller contribution relative to English (McBride-Chang et al., 2005). Although reading relies on the same core brain regions and cognitive skills across languages (Rueckl et al., 2015), children come to recruit these resources differently based on language-specific demands. In other words, language and linguistic structure influence children's mechanisms for reading.

The Role of Lexical Morphology

Morphology as a Bridge Between Language and Reading

The Lexical Quality Hypothesis posits that fluent word reading depends on closely interconnected mental representations of sound, meaning, and print (Perfetti, 2007). Prior to learning to read, young children have spent years developing spoken language skill and building close connections between representations of sound and meaning. How do young learners then connect their existing representations of spoken words to print?

In an extension of the Lexical Quality framework, Kirby and Bowers (2017) propose a **Binding Agent Theory**, which suggests that morphology is what connects representations of sound, meaning, and print to one another. At the single word level, morphology provides clues about word segmentation and pronunciation, as in the *s-h* sound(s) in *dishonest* as opposed to *dishwasher*. It also provides clues about meaningful relationships between words where phonology may not, as in *heal* and *health,* and the roles that words may play within a sentence context, as in *gladness* versus *gladly*. Morphology can thus be understood as an additional component of word knowledge that binds the other three constituents together.

Morphology in Word Reading and Reading Comprehension

Multiple theoretical frameworks suggest that morphological awareness plays an important role in the reading process. The **Reading Systems Framework** (Perfetti & Stafura, 2014) suggests that morphology contributes to literacy at both the single word and sentence level. First, and much like the Binding Agent Theory (Kirby & Bowers, 2017), morphology is conceptualized as a component of word knowledge, and supports single word recognition through the lexicon. Second, morphology is considered part of the general linguistic system, and contributes to comprehension processes more broadly. Empirical evidence in support of the Reading Systems Framework finds a direct contribution of morphological awareness to word reading, and both a direct and indirect contribution to reading comprehension, partially mediated by word reading (Deacon, Kieffer & Laroche, 2014). In sum, both the Binding Agent Theory (Kirby & Bowers, 2017) and Reading Systems Framework (Perfetti & Stafura, 2014) suggest that morphological awareness should play an important role in both single word reading and passage comprehension. At the single word level, morphology strengthens the connections between sound, meaning and print, likely enhancing lexical quality and word reading skill. At the sentence or passage level, morphology may also support overall comprehension by providing syntactic information about how words relate to one another.

In an examination of reading comprehension processes specifically, the **Active View of Reading** (Duke & Cartwright, 2021) situates morphological awareness as a "bridging process" that links word decoding skill with oral language proficiency. The Active View of Reading is an extension of the canonical Simple View of Reading model (SVR; Gough & Tunmer, 1986; Hoover & Gough, 1990). SVR suggests that reading comprehension is the product of decoding and language comprehension, which are framed as two separate skills. Morphological awareness, however, plays a role in both language comprehension and word recognition. Duke and Cartwright's (2021) updated framework highlights the overlap between these two constructs, and morphological awareness as one of the critical bridging processes that connects them in the mind of a learner.

Understanding Reading Development Through Different Populations

Language and Bilingualism

The theories of reading and reading comprehension reviewed thus far both highlight the importance of a child's general linguistic system (Perfetti & Stafura, 2014), or language knowledge (Duke & Cartwright, 2021) for reading. Importantly, there is natural variability in children's linguistic knowledge, related to differences in their language exposure, home environment and sociocultural context. These differences in linguistic knowledge and experience in turn impact reading development. For instance, earlier bilingual exposure has been positively associated with children's language proficiency, phonological awareness, and reading skill (Kovelman et al., 2008). By harnessing the existing natural variability in children's language experience and learning aptitude, we may better understand individual differences in reading across a broad swath of learners. More specifically, this dissertation examines variability in literacy development through the lens of bilingualism.

Understanding Bilingual Language Experience Along a Spectrum

Bilingual experience is multifaceted and difficult to quantify. As Grosjean warned the field in 1989, a bilingual is not "two monolinguals in one brain." At the same time, we must recognize that monolingualism and bilingualism are not qualitatively different experiences, but are perhaps best understood as opposite ends of a multidimensional spectrum (Luk, 2015). Binary categorization and comparisons of individuals as "monolinguals" versus "bilinguals" fails to account for variability in language usage, language proficiency, or age of acquisition. Careful attention to each of these dimensions allows us to probe how linguistic variation may influence literacy development.

Variation in children's linguistic systems may be further reinforced by reading experiences. This is because orthographies often accentuate the salient characteristics of their underlying languages. For instance, recall that Spanish is written with a phonologically transparent orthography in which units of print map directly to individual sounds, while in Chinese, units of print map onto morpho-syllables. We can therefore hypothesize that bilingual language experience in Spanish versus Chinese may bias young bilingual learners to pay greater attention to phonological or lexical features of English print, respectively.

English Literacy Development Through the Lens of Bilingualism

Emerging evidence suggests that the mechanisms underlying English reading vary as a function of bilingual children's heritage language backgrounds. For instance, young Spanish-English bilinguals show greater reliance on phonological as well as morphosyntactic skills when reading in Spanish as well as when reading in English, relative to English monolinguals (Kremin et al., 2016). In contrast, a study of Chinese-English heritage bilinguals demonstrated less reliance on phonological awareness and greater reliance on lexicosemantic knowledge when reading in English, relative to English monolinguals (Hsu et al., 2016). Reading development in children who speak more than one language may therefore reveal variability stemming from variation in the underlying structure of a child's specific languages (Hsu et al., 2016; Ip et al., 2016; Kremin et al., 2016). By studying linguistically diverse learners, both monolingual and multilingual, we may gain insight into the relations between spoken language experience and learning to read.

Learning Ability and Disability

Understanding Reading (Dis)ability Along a Spectrum

Much like language ability, reading skill can be similarly conceptualized as falling along a multidimensional spectrum. At one end of this spectrum lies very poor readers, those who demonstrate an unexpected difficulty in learning to read despite adequate intelligence and instruction. As successful reading requires the coordination and integration of numerous complex cognitive processes, there are many ways in which the reading process might break down. For instance, Child A might enter school with a large vocabulary but poor phonological awareness, leading to impaired single word recognition. Child B might be a skilled word reader, but struggle to comprehend connected text. Studying children with a reading impairment allows us to examine the system-wide impact of various mechanistic failures.

English Literacy Development Through the Lens of Reading Impairment

Developmental dyslexia (DD) is a specific learning disability in reading that is thought to affect between 5-17% of readers (Shaywitz et al., 2008). In particular, DD is typically characterized by impaired phonological processing and single word recognition. Phonological deficits in dyslexia appear to emerge early: infants who are later diagnosed with dyslexia show a reduced neural response to changes in speech sounds, in relation to infants who become typical readers (Leppänen et al., 2011). Similarly, preschoolers with high familial risk for DD consistently demonstrate poorer phonological skills than their peers who are not at risk for reading disability (Snowling & Melby-Lervåg, 2016). It is therefore likely that phonological skills are at the heart of impaired word recognition in dyslexia. In alphabetic languages such as English, this difficulty with sound processing is typically associated with difficulty forming sound-to-print associations, and may lead to impaired word reading ability.

Children may also struggle with reading comprehension specifically, independent of single word reading difficulties. This profile is generally referred to as specific reading comprehension deficit, or S-RCD (Landi & Ryherd, 2017). S-RCD is commonly associated with poor language skills, such as low vocabulary knowledge (Catts et al., 2006) and impaired performance on semantic tasks (Nation & Snowling, 1998; Nation et al., 1999). Notably, children with S-RCD are not impaired on phonology tasks, as would be expected of a child with dyslexia.

In addition to the different behavioral profiles of DD and S-RCD, the neurocognitive bases of these two reading disorders also diverge. Dyslexia has been associated with disrupted functional connectivity between the left IFG, which is involved in phonological processing and segmentation, and occipitotemporal regions involved in visual word form processing (Cutting et al., 2013). This reduced engagement of phonological processing regions is not limited to reading processes; children with dyslexia (Kovelman et al., 2012), or even preschoolers with familial risk for dyslexia (Raschle et al., 2012) under-engage left superior temporal regions during auditory rhyme processing.

In contrast, reading comprehension deficits have been linked to atypical connectivity between the IFG and subcortical regions associated with semantic memory (Cutting et al., 2013). Adolescents with S-RCD also show reduced activation in semantic processing regions such as the MTG and angular gyrus, and increased activity in regions associated with effortful retrieval during both spoken and written language processing (Ryherd et al., 2018). In a recent study by Ryherd and colleagues (2018), reading comprehension skill was positively associated with greater activation in the bilateral MTG, and negatively associated with engagement of the dorsolateral prefrontal cortex and subcortical regions.

In sum, there are multiple paths to successful reading development, as well as reading disability. This dissertation will consider the many ways in which children develop neurocognitive systems for reading, and the natural variation in the strength of their associations between sound, meaning, and print. Using a complementary brain-behavior approach, I examine typical and atypical learners from both monolingual and multilingual backgrounds, in hopes of furthering a comprehensive theoretical of reading acquisition across diverse learners.

Dissertation Studies

This dissertation is guided by the Lexical Quality Hypothesis (Perfetti & Hart, 2002; Perfetti, 2007), and the supposition that skilled reading requires efficient, simultaneous access to the correct representations of sound and meaning. The Lexical Quality model can be visualized as a triangle that connects representations of sound, meaning, and print. Binding Agent Theory (Kirby & Bowers, 2017) situates morphological awareness at the center of this triangle, as visualized in Figure I.2. The three dissertation studies that follow each probe a different edge of the triangular model. In particular, I question how children come to place varying emphasis on sound-based and meaning-based pathways, and how these mechanisms vary across individuals and developmental stages.

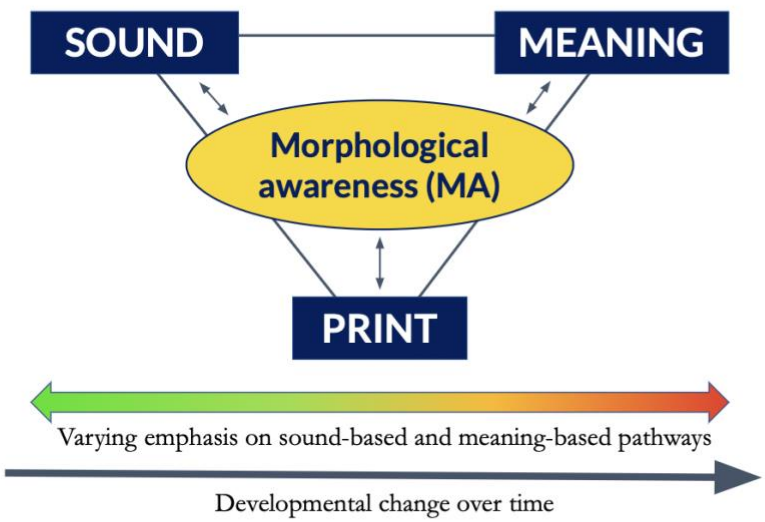


Figure I.2 *Theoretical framing of dissertation*

Study 1 examines the overlap in the neural mechanisms for accessing representations of word *sound* and *meaning* (when hearing words), and the mechanisms for accessing representations of *print* (when seeing words). The Lexical Quality Hypothesis (Perfetti, 2007) suggests that greater mechanistic similarity or overlap should be related to more proficient word reading. Guided by this framework, Study 1 examines the extent to which beginning readers use the same brain regions for hearing and reading words, and asks whether this neural overlap can predict reading outcomes one year later.

Building on this foundation, **Study 2** and **Study 3** shift from whole word processing to a more granular investigation of the sub-lexical constituents of word knowledge. In English, the smallest phonological and orthographic units that comprise a word are a single sound, or a single letter. Thus within the LQH model, mental representations of phonology and orthography are as granular as possible. However, as Perfetti and Hart (2002) acknowledge, semantics is conceptualized broadly. Lexical semantics includes knowledge of word meaning, structure, and grammatical features, and is often operationalized in terms of vocabulary knowledge. However, a single word may be broken down into smaller units of meaning, called *morphemes*. This dissertation advances a more precise theoretical understanding of lexical quality by focusing on *morphological awareness.*

In **Study 2,** I investigate the unique contribution of morphological awareness to emerging literacy at both the single word and passage level. Although a growing body of literature demonstrates the importance of morphological awareness for reading in upper elementary school and beyond, as children encounter an increasing number of unfamiliar multimorphemic words in academic texts (Gilbert et al., 2014; Goodwin et al., 2012; Kieffer & Lesaux, 2012; Singson, Mahony, & Mann, 2000), the relation between morphological awareness and reading in the early grades has been elusive (Apel et al., 2013; Desrochers, Manolitsis, Gaudreau, & Georgiou, 2018; Law & Ghesquière, 2017; Wolter et al., 2009). This study examines a gap in the literature, which has thus far suggested that sensitivity to units of meaning may not make a unique contribution to literacy for beginning readers. Study 2 aims to fill this gap and test the Lexical Quality

Hypothesis, which instead suggests that knowledge of both sounds and meanings should contribute to reading at any stage.

Study 2 further probes children's sensitivity to different types of morphological awareness, specifically awareness of derivations (e.g., *fruit+ful+ly)* and lexical compounds (e.g., *grape+fruit*). To hone in on variability across children, this study uses bilingual experience as a means of perturbing participants' exposure to different morphemic structures. In particular, I examine categorical differences between Spanish-English heritage language bilinguals, who have extensive experience with derivational morphology in Spanish, and Chinese-English heritage language bilinguals, who have extensive experience with lexical compounding in Chinese.

Finally, **Study 3** examines the neurocognitive mechanisms underlying morphological awareness, and their relation to literacy. The past several decades of educational neuroscience research have greatly informed our understanding of literacy acquisition, both in typical readers and readers with dyslexia, largely through an examination of phonological awareness and the brain basis of sound processing (Gabrieli, 2016). However, much less is known about the brain basis of morphological awareness, or how it may vary in impaired readers. Indeed, there is not yet a clear model of morphological processing in the brain, or how neural specialization for morphological awareness might support reading development. A recent meta-analysis (Leminen et al., 2019) concluded that the research to date offers "a fuzzy general picture about the mental operations underlying morphological processing, given that there is a notorious lack of consensus across research reports" (p. 37). There is thus a large gap in our understanding of brain development for morphological awareness, and its association with literacy acquisition. Accordingly, this dissertation study aims to examine both behavioral and neurobiological correlates of morphological awareness, and further illuminate how the brain basis of morphology may be associated with literacy in children across a broad range of reading skill.

Specific Research Questions

The specific research questions driving each of the three dissertation studies are visualized within the guiding theoretical framework in Figure 3 and detailed below. Individually, each dissertation study probes a different edge of the Lexical Quality triangular model to investigate young readers' emerging associations between sound, meaning, and print. Together, these studies shed light on how these associations vary across individuals and developmental contexts to influence literacy acquisition.

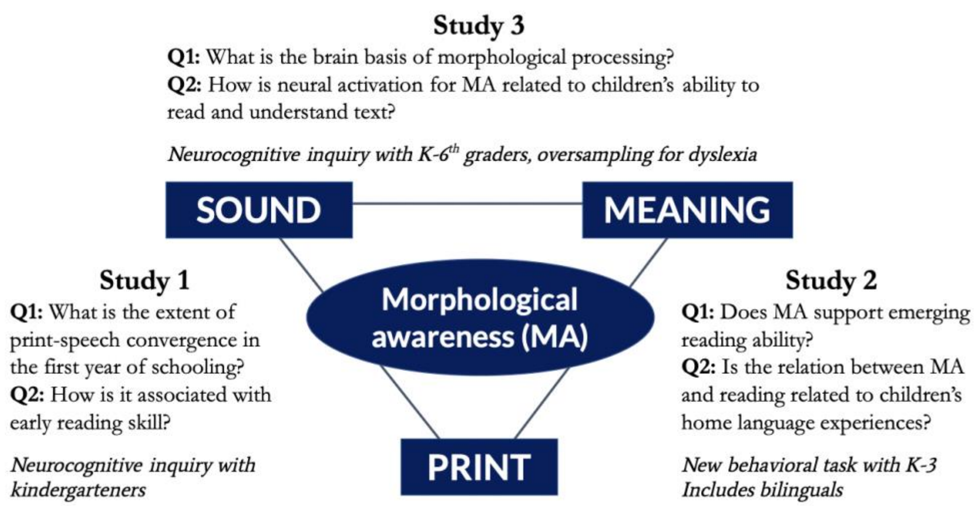


Figure I.3 *Specific research questions and methodological approaches of dissertation studies*

Study 1: How do spoken and written word processing relate at the beginning stages of literacy?

Over the course of learning to read, the brain develops pathways that link language with visual processing, allowing a reader to quickly recognize language in print. For a fluent reader, processing language in speech and in print are inextricably linked: proficient readers hear words when they read them, and often see words when they hear them. Indeed, adult readers around the world show remarkable similarity in brain activities for hearing words and reading words. Processing language in these two modalities relies on the same shared brain network (Rueckl et al., 2015). The aim of Study 1 is to examine the relationship between spoken language proficiency and the emergence of the print-speech network in beginning readers.

How do spoken and written language processing become so interconnected and interdependent? In this first dissertation manuscript, I examine the emergence of this shared brain network for processing language in speech and print, also called *print-speech convergence.* I ask three research questions: First, what is the relation between neural mechanisms for spoken and written language processes? Second, what cognitive abilities support this emerging relationship? Finally, how does print-speech convergence relate to future reading success? I hypothesize that the extent of children's print-speech convergence in kindergarten will be related to both their spoken language ability, and their early reading ability.

Study 2: How does children's sensitivity to units of meaning contribute to emerging literacy?

Building on the examination of whole word processing in speech and print in Study 1, Study 2 dives deeper into the granular components of word processing that support literacy acquisition. The goal of reading is not to simply recognize and be able to pronounce written words, but to understand their meaning. Accordingly, I focus on children's sensitivity to the smallest units of meaning in language, or their morphological awareness. Although morphology clearly contributes to literacy success in more advanced readers, the role of morphological awareness in the first years of schooling remains less well understood,

Study 2 aims to clarify the role of morphological awareness for early literacy and how it may vary across linguistically-diverse learners. I approach this aim through two interrelated studies. In Study 2A, I ask: How does morphological awareness contribute to children's concurrent English literacy throughout early elementary school? In Study 2B, I ask: How does bilingual experience influence the role of morphological awareness in English reading? I hypothesize that morphological awareness will make a significant, unique contribution to literacy in all readers, even in the beginning stages of literacy acquisition, and that the role of morphological awareness will vary as a function of children's cross-linguistic experiences. As theoretical frameworks suggest that morphological awareness may play multiple roles in the reading process (Perfetti & Stafura, 2014), Study 2 carefully examines both single word reading and reading comprehension in kindergarten through 3rd grade.

Study 3: What are the neurocognitive mechanisms underlying morphological processing, and how are they related to successful reading comprehension?

Building on Study 2, Study 3 examines the neurocognitive mechanisms underlying morphological processing, and their relation to reading and understanding connected text. I ask two research questions: First, what is the contribution of morphological awareness to reading comprehension in children across a broad spectrum of reading ability (both in typical readers and children with dyslexia)? Second, how are the brain bases of morphological awareness associated with skilled reading? I hypothesize that morphological awareness will be associated with children's reading comprehension across a broad spectrum of literacy skill, and that the neural correlates of morphological processing will vary as a function of reading (dis)ability. Together with Studies 1 and 2, this third manuscript aims to inform our understanding of the brain basis of spoken language processing and its relation to successful reading development.

CHAPTER II. Spoken Language Proficiency Predicts Print-Speech Neural Convergence

Learning to read transforms the brain (Dehaene et al., 2010, 2015). Specifically, recognizing words in their written form engages two key components: language proficiency, and visuospatial processing. The cross-modal integration of these auditory and visual processes results in a brain network of frontal, temporal, and parietal regions that is activated during both auditory word (speech) and visual word (print) processing, across languages and orthographies (Rueckl et al., 2015). This co-active network for auditory and visual language processes, also called *print-speech convergence*, is thought to emerge as a function of learning to read (Chyl et al., 2018). However, the cognitive abilities that precede and predict the emergence of this shared network, setting the stage for successful reading acquisition, remain unknown.

Reading acquisition presents a paradox. Despite the lengthy neurodevelopmental trajectory towards reading fluency (Turkeltaub et al., 2003), it is well established that children's spoken language skills precede and predict reading outcomes long before literacy instruction. For instance, children's vocabulary prior to age two significantly predicts word reading accuracy and reading comprehension five years later (Duff et al., 2015). By age 2½, children who later exhibit reading disorders demonstrate poorer spoken language ability than typical readers (Scarborough, 1990). Similarly, preschool children with family risk for dyslexia, a highly heritable, lifelong reading impairment, consistently demonstrate poorer phonological and syntactic skills than their peers who are not at risk for reading disability (see meta-analysis by Snowling & Melby-Lervåg, 2016). Furthermore, preschoolers' sensitivity to word sounds (e.g., rhyme and alliteration) predict reading and spelling three years later (Bradley & Bryant, 1985), while language skills at age 8 predict reading skills in adolescence (Nation & Snowling, 2004). Thus, young children's language ability is strongly associated with their reading success years later.

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

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

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

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

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

Method

Participants

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

Inclusion Criteria for Neuroimaging Analysis

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

Longitudinal Participants

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

Measures

Neuroimaging Measures

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

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

The words used in the fMRI tasks were high frequency nouns, typically acquired prior to age five according to two age of acquisition indices (Gilhooly & Logie, 1980; Kuperman et al., 2012). All words had one or two syllables, and were an average of 4.23 phonemes long. Stimuli were matched for the number of syllables and phonemes within each word pair. Words were phonologically and visually distinct from one another within non-matching pairs (e.g., “cherry” –

"puzzle"). Because participants were beginning readers, stimuli used in the visual word matching task were chosen from pictures of kindergarten classrooms with high frequency words on the walls (e.g., house, dog, pencil, birthday), and from publicly available 1st and 2nd grade spelling lists, to ensure their familiarity. T-tests showed no significant differences in phoneme length, age of acquisition, familiarity, written frequency or imagability between words that appeared across tasks, or in matching as compared to non-matching pairs. All neuroimaging stimuli are presented in Appendix A.

Behavioral Literacy Measures

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

Procedure

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

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

fMRI Acquisition Parameters

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

Data at Site 1 were acquired with a 3-T Siemens TRIO whole-body MRI scanner using a 32-channel whole-head coil. Whole-brain functional images were acquired using a gradient-echo echo-planar pulse sequence [repetition time (TR) = 2000 ms, echo time (TE) = 28 ms, flip angle

(FA) = 80º, field of view (FOV) = 230 mm, voxel size = 2.4x2.4x3.6 mm, 32 contiguous 3.6-mm axial slices, 0-mm inter-slice gap]. Prior to each scan, seven volumes were discarded to allow T1-Equilibration effects. Within each functional run, the inter-trial intervals corresponding to the MR frames served as baseline or null events (i.e., fixation cross presented in the center of the screen). After the scanner upgrade, image acquisition at Site 2 (N = 56) was carried out using a 3-T Prisma Fit MRI scanner equipped with a 64-channel head coil. Whole-brain functional images were acquired using a gradient-echo echo-planar pulse sequence [TR = 1250 ms, TE = 33.40 ms, FA = 45º, FOV = 220 mm, voxel size = 2.2 mm^3, 64 contiguous 2.20-mm axial slices, 0-mm inter-slice gap]. Prior to each scan, 11 volumes were discarded to allow T1-Equilibration effects. High-resolution T1-weighted anatomical images were collected at both sites with the same acquisition parameters: matrix size 256 × 256; 160 contiguous axial slices; voxel resolution 1 mm; TR = 2300ms, TE = 2.98ms, T1 = 900ms; and FA = 9°.

fMRI Data Processing and Analysis

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

Group-Level Analyses. Data from each participant were entered into two general linear models: one for speech processing, and one for print processing. Participants' BOLD response for each block of word pairs was modeled using a canonical hemodynamic response function (HRF), and averaged to generate statistical images for word processing > rest contrasts. We used second-level GLM analyses to obtain group-level contrasts, controlling for scanner differences, participant age, maternal education, and familial risk of dyslexia. We examined these contrasts using independent sample *t*-tests for whole-brain activation at an FDR corrected threshold of $q = .01$, and a cluster threshold of 62 as recommended by 3dClustSim ($\alpha < .10$). A group-level intersect map of converging print- and speech-related activation was constructed with 3dcalc using the output of the group analyses, with a combined threshold of $q = .0001$, $\alpha < .01$.

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

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

Results

All 133 participants were typically developing native speakers of English, with varied levels of exposure to other languages. Mean standard scores on assessments of expressive and receptive vocabulary, oral comprehension, phonological awareness, morphological awareness, decoding, word reading, and reading comprehension were all within the normal range for 5–6-year-old children (Table II.1). Correlations between these measures are presented in Table II.2. We observed typical word reading ability for children in the first year of schooling (mean standard score = 95.76, SD = 12.81). 13% of our participants could only identify letters (e.g., *k*, *L*), and 72% could read high frequency monosyllabic words (e.g., *car*, *she*). The remaining 15% could read more complex words (e.g., *animal*, *become*). The associations between children's language

Table II.1 Standard scores of language and literacy skills.

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

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

Table II.2 Partial correlations between language and literacy measures.

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

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

and literacy skills are detailed in Table 2. Children with usable, high-quality neuroimaging data from both tasks were likely to be from a slightly higher socioeconomic status (mean years of maternal education = 17.4 vs. 16.8, $t(132) = 2.24$, $p < .05$). However, there were no significant differences in age, language proficiency, or reading ability between the children who were and were not included in fMRI analyses.

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

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

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

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

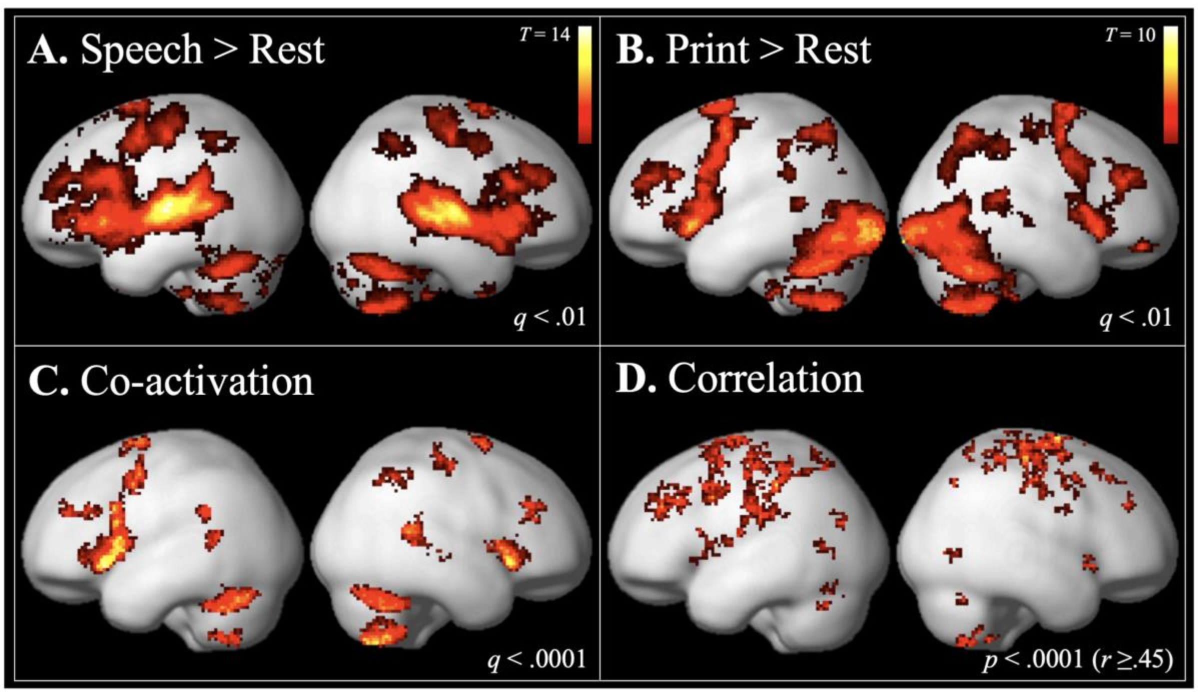


Figure II.1 Kindergarten brain activation for speech processing, print processing, and shared across modalities.

Co-active Brain Regions for Print and Speech. To uncover the shared cortical regions engaged during both print and speech processing, we conducted a whole-group intersect analysis. Results revealed that both auditory and visual word processing recruited frontal and temporal regions, including bilateral IFG/insula and bilateral STG/MTG, as well as the bilateral precentral gyrus and supramarginal gyrus extending into inferior parietal lobule (IPL; Figure II.1C). Additionally, both tasks engaged the bilateral anterior cingulate, MFG and SFG. Other overlapping clusters of activity are detailed in Table 3.

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

	Peak MNI coordinates				Cluster size
Regions	*x*	*y*	*z*	*Z*	Voxels
Speech Processing					
Bilat. STG, MTG, IFG, insula	-67	-13	7	7.03	19,262
Bilat. cerebellum (Crus I, VI), FG	-47	-59	-23	3.82	5,317
Bilat. superior/medial frontal, SMA, cingulate	-1	1	57	6.82	3,838
R pre/post central gyrus	43	-19	67	2.39	649
Bilat. lingual gyrus, cuneus	-3	-73	1	3.21	379
L cerebellum (VIII)	-23	-63	-61	3.76	342
R IPL	53	-55	53	3.21	181
L MFG/SFG	-35	45	35	3.15	141
L IPL	-61	-43	51	3.13	123
L cerebellum (IX)	-13	-53	-33	4.15	64
Bilat. cingulate gyrus	1	-29	27	3.03	64
Print Processing					
Bilat FG, ITG, MOG, cerebellum (Crus I, V)	45	-67	-21	4.22	11,742
Bilat. medial frontal, SFG, SMA, cingulate	-7	3	75	3.57	5,633
L thalamus, caudate, IFG, insula	-1	-13	13	2.6	4,877
R IFG, insula, thalamus, caudate	49	21	-9	3.57	1,867
R SPL/IPL	37	-63	59	3.78	1,856
L SPL/IPL	-27	-73	57	3.06	1,532
L cerebellum (VII, Crus 2)	-29	-77	-57	3.44	660
R MFG	43	43	31	3.36	448
R STG, MTG	51	-41	15	3.8	421
L MFG, SFG	-31	57	27	3.02	314
R lingual gyrus, cuneus	25	-63	5	3.34	211
L cuneus	-7	-75	13	4.09	145
Bilat. cingulate gyrus	1	-29	27	3.44	140
R pre/post central gyrus	37	-23	69	3.36	138
L MFG, IFG	-49	25	29	3.25	130
R hippocampus	31	-23	-9	3.42	118
L STG, MTG	-57	-51	13	3.78	98
L SMG/IPL	-61	-43	25	4.41	81
L hippocampus	-35	-21	-11	4.67	74
R SPL, precuneus	11	-71	51	3.02	67

Print-Speech Co-Activation	Center of mass *x*	*y*	*z*		Voxels
Bilat. medial frontal, SFG, SMA, cingulate	0	13	49	-	3322
Bilateral cerebellum (VI, V, VIII)	2	-64	-25	-	3057
L insula, IFG	-42	16	7	-	1314
L thalamus, putamen	-13	-4	3	-	1236
R insula, IFG	39	21	1	-	645
R cerebellum (VIII)	30	-61	-52	-	637
R putamen	18	12	4	-	499
R STG, MTG	52	-37	9	-	328
L precentral gyrus, MFG	-46	-1	49	-	210
R thalamus	13	-15	9	-	169
L cerebellum (VI, VIII)	-34	-59	-52	-	154
R MFG, IFG	43	35	27	-	119
Right IPL	41	-53	46	-	117
R precentral gyrus	38	-21	57	-	112
L cuneus	-11	-75	11	-	85
L STG, MTG	-53	-50	10	-	84
R posterior cingulate, cuneus	13	-70	12	-	78
L SMG, IPL	-58	-44	27	-	75
L MFG	-34	41	28	-	69
L IPL	-47	-50	49	-	63

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

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

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

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

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

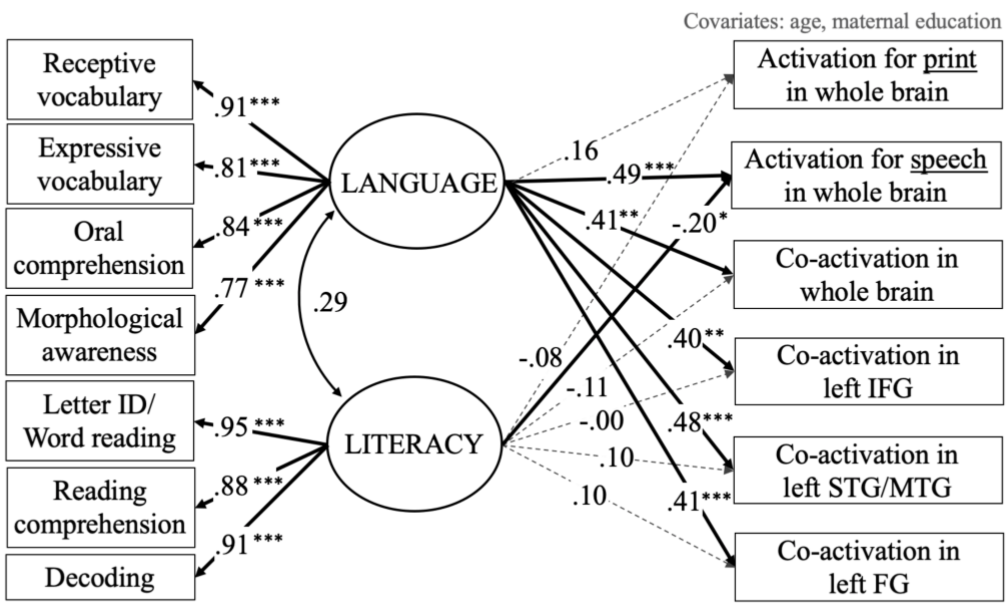


Figure II.2 *Structural model explaining number of active voxels for print, speech, and print-speech co-activation.*

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

Table II.4 Regression explaining print-speech correlation in MTG from language skill.

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

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

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

Table II.5 Regression explaining 1st grade reading from kindergarten print-speech co-activation.

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

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

Table II.6 Regression explaining 1st grade reading from kindergarten word reading and kindergarten print-speech co-activation.

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

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

Discussion

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

These findings extend our understanding of brain development for literacy at the onset of reading instruction, and suggest a developmental continuity from children's neural organization for spoken language processing to the gradual reorganization for reading.

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

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

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

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

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

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

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

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

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

CHAPTER III. Morphological Awareness Contributes to Early Reading

As children learn to read, they encounter increasingly complex new words. Across languages, new words are primarily formed through two common principles. First, we can add prefixes and suffixes to root words (e.g., *un*-break-*able*) in a process called derivation. Second, we can combine roots to create a compound word with a new meaning (e.g., *heart-break*, *break-down*). Children's sensitivity to units of meaning in language, also called *morphological awareness*, plays a critical role in successful literacy, especially once children master basic word reading (Carlisle, 2000; Goodwin et al., 2013; Nagy et al., 2006; Singson et al., 2000). However, the role of morphological awareness in early English reading development remains less clear (e.g., Apel et al., 2013; Law & Ghesquière, 2017).

The Reading Systems Framework suggests that morphology plays multiple roles in the reading process (Perfetti & Stafura, 2014). First, morphology is integral to each individual word, and so knowledge of morphemes contributes directly to single word identification. Second, morphology is also part of a child's general linguistic system, and thus influences comprehension processes more broadly. Yet while theories of reading generally assume knowledge of a single linguistic system, there is great variation in children's language backgrounds especially as a factor of bilingual and cross-linguistic experiences. Furthermore, languages vary in their morphological structure. For instance, Spanish and other Romance languages rely primarily on derivational morphology, while Chinese relies primarily on lexical compounding. Moreover, cross-linguistic comparisons suggest that morphological awareness in English may be slower to develop than in languages with a more predictable morpho-phonological structure (e.g., French; Duncan et al., 2009). It is therefore possible that children's bilingual experiences may affect their morphological awareness, or sensitivity to specific morphemic structures, influencing the reading process in English. By studying linguistically diverse learners, we may gain insight into the relations between spoken language experience, morphological awareness, and learning to read.

Accordingly, the present chapter aims to answer two unresolved questions about morphological awareness and early English literacy in linguistically diverse learners. First, how does awareness of derivational and compound morphology contribute to children's emerging literacy skills in kindergarten through 3rd grade? Second, how does bilingual experience with structurally distinct languages influence the relation between derivational and compound awareness and early reading? Together, these inquiries aim to shed light on the mechanisms underlying English literacy across linguistically diverse learners, and advance cross-linguistic theories of reading development.

Defining Morphological Awareness

We must first acknowledge that the terms "morphological awareness" has been used broadly, and often encompasses a spectrum of cognitive abilities. Some explicitly define morphological awareness as a conscious or explicit understanding of the morphemic structure of words (Carlisle, 1995; Jarmulowicz et al., 2008; Kirby et al., 2012; Tong et al., 2011). Yet children are able to manipulate units of meaning (morphemes) in speech long before they can demonstrate strategic use of morphological awareness (Berko, 1958). This tacit understanding of morphology is often considered a component of morphological awareness. However, others have made distinctions between explicit morphological awareness, and implicit morphological processing (Nagy et al., 2014), morphological production (Apel et al., 2013), and morphological analysis (Deacon, Tong, & Francis, 2017). In the present study, we employ a commonly-used type of morphological awareness assessment (Carlisle, 2000; Goodwin et al., 2012) which captures children's ability to manipulate morphemes in speech as early as age 5. Therefore, we adopt Carlisle's inclusive definition of morphological awareness, denoting its existence on a continuum from implicit awareness to an explicit understanding of morphology over the course of schooling and development (Carlisle, 2004). As part of our inquiry, we explore the nature of the task and its current definition in relation to children's sentence processing skills and cognitive abilities.

Cross-Linguistic Perspectives on Morphological Awareness and Learning to Read

Learning to read varies across languages. Psycholinguistic Grain Size Theory (Ziegler & Goswami, 2005) suggests that orthographies vary in the size of the linguistic unit that is key for reading success. In alphabetic languages, letters correspond to individual sounds. When these sound-to-letter mappings are highly consistent, such as in Spanish, Italian or Greek, readers can use smaller grain sizes (individual phonemes) to access the larger morphemic units early in reading acquisition (e.g., Manolitsis et al., 2017). In Chinese, written characters correspond to units of meaning, rather than units of sound. This morpheme-to-print mapping provides readers with direct access to word meaning. Children's morphological awareness is thus one of the most powerful predictors of early Chinese word reading (McBride-Chang et al., 2003).

English, in contrast, is morphophonological – spellings are based on both units of sounds and units of meaning (Carlisle & Addison, 2005). Although English is alphabetic, the sound-to-letter mapping is notoriously inconsistent. In some cases, one letter may have multiple sounds (such as the *c* in *click, check* or *circle*), while one phoneme might be spelled multiple ways (such as the */k/* sound in *castle, kitten, locker*, and *echo*). This inconsistency makes it difficult for beginning readers to decode common, mono-morphemic words like *people* or *through.* In other cases, spelling might remain consistent across words to maintain the underlying morphemic structure, even when the phonology changes (e.g., *music-musician* or *heal-healthy*). Although these morphemes may be easily identified in print, they are challenging to recognize in speech due to the change in pronunciation.

This creates a paradox for the English reader. On the one hand, large grain sizes are key to decoding English words. On the other hand, these larger grains may be difficult to access, given the phonological and orthographic complexity of the language. To compound this issue further, morphemic regularities may not be obvious in spoken English due to differences in pronunciation. Although morpheme recognition is critical for successful literacy, neither spoken nor written English lends itself to extracting morphemes easily.

Theoretical models suggest that English readers only begin to recognize morphemic units in the consolidated alphabetic phase of development, after they have mastered sound-to-print correspondences and are able to decode words (Ehri, 1995, 2014). However, given that morphology is integral to each and every word, it is logical that morphology should play a role in beginning, as well as more proficient, word reading. Furthermore, we know that morphological awareness is associated with early word reading in both more phonologically-transparent alphabetic languages such as Dutch (Rispens et al., 2008) or Greek (Manolitsis et al., 2017), and more morphologically-transparent languages such as Chinese (Pan et al., 2016). English sits between these two languages along a spectrum of orthographic transparency, and yet, the role of morphology in early English word reading is less clear. This places English at a critical juncture for understanding the role of morphological awareness in literacy acquisition across languages, particularly for emerging readers.

The present chapter aims to answer two questions. First, how does awareness of derivational and compound morphology contribute to children's concurrent English literacy throughout early elementary school? Second, how does bilingual experience with distinct morphological structures, such as derivational morphology in Spanish, or lexical compounding in Chinese, influence the role of morphological awareness in English reading? In Study 2A, we tested the prediction that morphological awareness would be related to children's concurrent word reading and reading comprehension skills in beginning readers in kindergarten through 3rd grade. In Study 2B, we examined how children's awareness of compound and derivational morphology might vary as a function of their bilingual background, and whether this morphological awareness might differentially contribute to their English literacy. We hypothesized that dual-language proficiency would lead to cross-linguistic transfer, affecting a child's general linguistic system and sensitivity to certain grain sizes, thereby influencing the reading process in English. Together, Study 2A and Study 2B shed light on the contribution of morphological awareness to early reading across linguistically diverse learners.

Study 2A: Morphological Awareness and Emerging English Literacy

Children's understanding of morphology in English begins to emerge in infancy, and continues to mature through middle and high school (Kuo & Anderson, 2006). First, children begin to recognize and master the rules governing inflectional morphology, which uses a limited number of morphemes to indicate grammatical function (e.g., *create-s, creat-ing, creat-ed*). Young children also learn to manipulate morphemes in order to create new words, either through lexical compounding or derivation. In English, compounding emerges first. Children as young as 18 months create novel lexical compounds by combining two words to fill gaps in their vocabulary (Clark, 1993), such as *nose-bangs* for a moustache. An understanding of derivational morphology (e.g., *re-create, creat-ive*) emerges slightly later, and continues to develop throughout middle and high school (Kuo & Anderson, 2006).

Derivational morphological awareness plays a particularly important role in literacy. Children encounter an increasing number of derived word forms in academic texts as they progress through school (Nagy & Anderson, 1984).At the single word level, prior work has revealed an increasingly robust association between derivational morphological awareness and word reading throughout elementary and middle school (Carlisle & Kearns, 2017; Roman et al., 2009). For instance, awareness of derivational suffixes makes an increasing contribution to word reading in 3rd through 6th graders (Singson et al., 2000). However, it has been relatively difficult to characterize the relation between morphological awareness and concurrent word reading in younger children. This may be due in part to the long-standing challenge of finding an appropriate measure of derivational morphology that is accessible to 5–6-year-old children as well as slightly more advanced readers.

Because of the relative difficulty of manipulating derivational morphemes in English prior to learning to read, many scholars have combined inflectional and derivational morphology in their tasks for young children (Apel et al., 2013; Kirby et al., 2012; Law & Ghesquière, 2017; Wolter et al., 2009). For instance, Kirby and colleagues (2012) administered a morphological analogy task longitudinally in 1st through 3rd grade. Despite combining both inflectional and derivational morphology, children's mean accuracy in 1st grade near floor level, and was not correlated with future reading measures (Kirby et al., 2012). The same measure administered in

2nd and 3rd grade was highly correlated with 3rd grade reading outcomes, suggesting that while morphological awareness may contribute to reading development, this task was not accessible to younger participants.

Several other studies have found inconsistent relationships between morphological awareness and early English reading, using a variety of methodological approaches. Apel and colleagues (2013) asked children to produce an inflected or derived form of a given base word (e.g., *Wind*. *Before a storm, it gets*… [correct answer: *windy*]). Children's performance on this measure was inconsistently related to concurrent reading ability: it was positively associated with single word reading in kindergarten and 2nd grade, but not in 1st grade (Apel et al., 2013). Similarly, Law and Ghesquiere (2017) found that kindergarteners' morphological awareness was positively correlated with their 1st and 2nd grade word reading. However, much like Apel et al., (2013), the same measure of morphological awareness in 1st grade was not related to concurrent reading. At the same time, Wolter and colleagues (2009) revealed an association between morphological awareness and word reading in 1st grade, above and beyond the contribution of phonological awareness, and others have revealed longitudinal associations with later word reading (Deacon et al., 2018; Kruk & Bergman, 2013). Morphological awareness has thus proven a promising but elusive contributor to early word reading.

Much like single word reading, derivational morphological awareness also plays a key role in reading comprehension, particularly in late elementary school, middle school, and beyond. In support of the Reading Systems Framework (Perfetti & Stafura, 2014), Deacon and colleagues have demonstrated that morphological awareness is directly associated with word reading in 3rd and 4th grade, and that word reading partially mediates the relationship between morphological awareness and reading comprehension (Deacon et al., 2014). Children with poor reading comprehension in 5th grade differed in their morphological derivation skill (but not morphological inflection) compared to their peers with average or advanced reading comprehension (Tong et al., 2011). Even among beginning readers, derivational morphology assessed at age 5-6 explained unique variance in reading comprehension two years later (Deacon et al., 2018). Nevertheless, some prior work with 2nd-5th graders has suggested that morphological awareness does not predict unique variance in reading comprehension above the contribution of single word reading (Gilbert et al., 2014; Goodwin et al., 2013; Proctor et al., 2012) or vocabulary (Silverman et al., 2015).

In sum, the role of morphological awareness in word reading and reading comprehension, particularly among beginning readers, is still not entirely clear. Furthermore, while many studies have indicated the importance of derivational morphology for English literacy, the role of compound morphology remains unexplored. Lexical compounding is one of the earliest emerging morphological skills (Clark, 1993), yet tests of compounding are missing from the lions' share of English morphological awareness tasks.

The primary aim of Study 2A was to clarify the contribution of derivational and compound morphological awareness to concurrent English literacy during this uncertain developmental period, from the first year of formal schooling through grade 3. To do this, we first modified an existing measure of morphological awareness to be more accessible to beginning readers (Extract the Base; Goodwin et al., 2012). Most notably, we expanded the assessment to include compound morphology (e.g., *team-work, foot-ball*), in addition to derivational morphology (e.g., *quick-ly, argue-ment*). This design was intended to capture a wider breadth of English morphology, and ensure that the task was accessible to our youngest readers. Furthermore, the inclusion of both derivational and compound morphology mirrored the morphemic characteristics of our bilingual participants' home languages (derivationally-rich Spanish, as well as compound-rich Chinese), as explored in Study 2B. Guided by Reading Systems Framework (Perfetti & Stafura, 2014), we predicted that both derivational and compound morphological awareness would make an independent contribution to literacy at the single word and sentence level. We tested this prediction by performing two hierarchical regression analyses to examine the unique contribution of morphological awareness to single word reading and reading comprehension abilities.

Method

Participants and Procedure

Three hundred and ninety-five children, ages 5-9 participated in our study. All participating children were in grade 3 or below. To be included in data analysis, children were required to be proficient English speakers with at least elementary word reading ability (details below). Exclusion due to low English proficiency or word reading ability left a final sample of $N = 340$ children (188 boys, 152 girls; $M_{age} = 7.39$ years old, $SD = 1.06$). Participants were of varied racial and ethnic backgrounds: the sample was 36% White, 28% Asian, 18% Latinx, 16% Multiracial, and 3% Black. Children came from highly-educated backgrounds, with 89% of mothers having a college degree or above. Demographic characteristics for all participants are presented in Table 1.

Participants were recruited as part of two larger neuroimaging studies of bilingual reading development from a college town in the Midwestern United States ($N = 229$, age range = 5.12-9.74) and a large urban center on the West coast ($N = 111$, age range = 6.48-8.76). We therefore intentionally recruited monolingual and bilingual populations, targeting heritage language schools and bilingual community centers. According to parent report, over half of our sample

Table III.1 *Demographic characteristics of participants in Study 2A and Study 2B*

	Study 2A (*n* = 340)		Study 2B (*n* = 207)	
Variable	n	%	n	%
Sex				
Male	188	55.3	110	53.1
Female	152	44.7	97	46.9
Grade				
Pre-K – K	68	20.0	50	24.2
1st	137	40.3	77	37.2
2nd	88	25.9	50	24.2
3rd	47	13.8	30	14.5
Language				
English monolingual	146	42.9	69	33.3
Spanish-English bilingual	92	27.1	69	33.3
Chinese-English bilingual	96	28.2	69	33.3
Other home language(s)	6	1.8	0	0
Race and ethnicity				
American Indian or Alaska Native	1	0.3	0	0
Asian	84	27.6	63	30.4
Black or African American	10	2.9	9	4.3
Hispanic or Latinx	61	17.9	54	26.1
Multiracial or Multiethnic	54	15.9	35	16.9
White or European American	121	35.6	46	22.2
Maternal educational attainment				
No high school diploma	6	1.2	6	2.9
High school or GED	9	2.6	6	2.9
Some college	13	3.9	8	3.8
Associate's degree	10	2.9	5	2.4
Bachelor's degree	100	29.4	64	31.5
Some graduate school	8	2.4	6	2.9
Master's degree	137	40.3	76	36.7
Professional or doctoral degree	51	15.0	32	15.5
Missing data	6	1.8	4	1.9

spoke a language other than English at home (27% Spanish, 28% Chinese, 2% other). All children were also highly proficient speakers of English, as defined by standard vocabulary scores above 85 on the Peabody Picture Vocabulary Test (Dunn, 2018; Dunn & Dunn, 2007).

Bilingual participants should therefore be considered dual first-language learners, and *not* English Language Learners (ELLs).

Standardized Measures of Language and Literacy

Receptive vocabulary was assessed using the Peabody Picture Vocabulary Test (PPVT). Participants on the West coast were assessed using the PPVT-4 (Dunn & Dunn, 2007) as part of a larger, longitudinal study that began in 2015. Data collection at the Midwestern site began in 2019, using the updated PPVT-5 (Dunn, 2018). In order to be eligible for the present study, children had to be proficient English speakers as defined by a standard score of 85 or above. Thirty-one children out of the full sample of 395 (3 monolinguals and 28 bilinguals) were excluded due to low English vocabulary.

In addition to the English receptive vocabulary measure, Spanish-English bilingual participants completed the Test de Vocabulario en Imágenes (Dunn et al., 1986), while Chinese-English bilingual participants completed the Peabody Picture Vocabulary Test – Revised in Chinese (Lu & Liu, 1998).

Emerging literacy skills were operationalized as single word reading ability and reading comprehension. *Single word reading* was assessed using the Letter-Word Identification subtest from the Woodcock Johnson IV Tests of Achievement (Schrank et al., 2014a). The first test items require children to identify letters, and later items ask children to read single words of increasing complexity. In order to be eligible for the present study, children were required to have a raw score of 14 or above, indicating that they could successfully name letters and identify at least four high frequency words such as *dog* or *the*. Twenty-four children out of the remaining sample (15 monolinguals, 9 bilinguals) were excluded due to low word reading ability, leaving a final sample of $N = 340$ participants.

Reading comprehension was assessed using the Woodcock-Johnson Passage Comprehension subtest (Schrank et al., 2014). This task measured comprehension of connected text. For beginning readers, the Passage Comprehension task is heavily supplemented by pictures, while more advanced items require children to read a sentence or passage and fill in a missing word.

Phonological awareness was assessed using the Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP-2; Wagner et al., 2013). Children are asked to pronounce a word while removing a phonetic unit, starting at the syllable level (e.g., "Say *toothbrush* without saying *tooth*") and progressing to single phonemes (e.g., "Say *winter* without saying */t/*"). Scaled scores on this phonology measure have a mean of 10; scaled scores between 8-12 fall within the typical developmental range.

Task of Morphological Awareness

We developed an experimental task of derivational and compound morphology built upon the decomposition task model (Carlisle, 2000). In this model, children are asked to extract the base of a multimorphemic word in order to complete a sentence. In particular, task development was based on the Extract the Base task by Goodwin and colleagues (2012), which was extensively piloted and validated with a large group of linguistically diverse 3rd to 5th graders. Building upon this model, we modified the task items and structure to make it easier for young children. We call our modified task the Early Lexical Morphology Measure (ELMM).

To ensure that our measure was accessible to pre-readers as well as readers, the task was administered entirely orally, with no visual or written component. To introduce the task, the experimenter told each participant, "I will say a word, and then you will use *part* of that word to help me finish my sentence." The experimenter then said a multimorphemic word, followed by an incomplete sentence (e.g., *Friendly. She is my best…*_____). Children were expected to complete the sentence using the root word (e.g., *friend*). Participants received feedback on this training item. No feedback was given on subsequent testing items, which were presented in a fixed order. Testing was discontinued if the child made 10 consecutive errors.

We made a few notable changes to the Extract the Base task (Goodwin et al., 2012). First, as discussed, we expanded the assessment to include compound morphology in addition to derivational morphology. We further redesigned existing task items to place all target words at the end of a simple sentence, thereby reducing working memory load, and replaced later-acquired, academic vocabulary with earlier-acquired words. For instance, instead of asking children to extract the base *fear* from *fearful,* or *dense* from *density,* children extracted *color* from *colorful* and *person* from *personality.* This change was intended to make the task more accessible to young children.

Our Early Lexical Morphology Measure (ELMM) was comprised of 40 items (15 compound, 25 derived). Five derivational items were identical to those in Goodwin's (2012) measure. Six were modeled on items from Goodwin and colleagues (2012), but used a modified sentence prompt that was more accessible to young children. For instance, instead of the prompt, "*Combination.* Which chemicals should I ___?" our participants heard, "Which colors should the painter ___?" The final task also included 29 newly developed items, 15 of which assessed compound morphology (see Appendix B).

To examine the dimensionality and internal consistency of the ELMM, we ran two confirmatory analyses using a weighted least square mean and variance adjusted (WLSMV) estimator, allowing for full information maximum likelihood (FIML) estimation of missing data. The goal of these analyses was to compare a two-factor model, in which derivations and compound items loaded onto separate constructs, as opposed to a one-factor model with a single underlying morphological awareness construct. The two-factor model yielded a good fit (χ^2(741, *N* = 339) = 1307.80, RMSEA estimate = .05, CFI = .94, TLI = .93, SRMR = .13). To our surprise, however, the one-factor model was an excellent fit for our data (χ^2(741, *N* = 339) = 905.71, RMSEA estimate = .03, CFI = .98, TLI = .98, SRMR = .10), suggesting that both derived and compound items on the ELMM tapped into a single underlying cognitive ability. The Cronbach's alpha reliability coefficient was .93, indicating good internal consistency.

Because of our focus on the role of compound and derivational awareness in younger readers, the current study presents data from the full ELMM measures, as well as from a subset of 13 compound and 13 derived items with base words acquired prior to age 6. Of these 26 items of interest, the multimorphemic prompt words had a mean age of acquisition (Kuperman et al., 2012) of 5.60 (*SD* = 1.50), while the base words had a mean age of acquisition of 4.75 (*SD* = 1.25). Independent sample *t*-tests confirmed that there were no significant differences between root morphemes in derived versus compound items in terms of their age of acquisition ($t(24) = 1.62$, $p = .119$; Kuperman et al., 2012), frequency in child-directed speech ($t(24) = -1.43$, $p = .165$; MacWhinney, 2000), nor frequency in adult speech ($t(24) = -1.07$, $p = .297$; Davies, 2008). We therefore present data from the full 40 ELMM items when examining morphological awareness as a single construct, and data from the 26 matched, early acquired derivations and compounds when testing a priori hypotheses about derivational versus compound morphological awareness.

Results

Descriptive Analysis

All 340 eligible children, ages 5-9, participated in Study 2A. Twenty percent of this sample was enrolled in junior kindergarten or kindergarten (*N* = 68, M_{age} = 6.01), 40% was in 1st grade (*N* = 137, M_{age} = 7.05), 26% was in 2nd grade (*N* = 88, M_{age} = 8.17), and 14% was in 3rd grade (*N* = 47, M_{age} = 8.92). All participants were highly proficient speakers of English with standard vocabulary scores above 85 on the Peabody Picture Vocabulary Test (Dunn, 2018; Dunn & Dunn, 2007). The sample included monolingual English speakers and dual first-language learners who spoke a language other than English at home. The breakdown of children's home language background by grade is provided in Appendix D, Supplementary Table D.4.

The participants in the study had high-average English language and literacy skills, with mean standard scores ranging from 105 to 113. Table III.2 provides descriptive statistics as well as the Pearson correlations between each measure. The ELMM was correlated with all standardized measures of language and literacy. The strongest relationship was between morphological awareness and reading comprehension, $r(339) = .71$, $p < .001$. Note that the 13 early-acquired derived items and 13 early-acquired compound items were both significantly associated with literacy outcomes, with correlation coefficients ranging from .59 - .66 (Table 2). Fisher *r*-to-*z* transformations revealed no meaningful difference in the strength of association between derivations and compounds to word reading ($z = 0.84$, $p = .401$) or to reading comprehension ($z = 1.26$, $p = .208$).

The ELMM task was accessible to 5-year-old kindergarteners as intended, sensitive to developmental differences in children ages 5-9, and reliable across all grade levels (K = .86, 1st =

.88, 2nd = .90, 3rd = .75). A one-way analysis of variance (ANOVA) confirmed significant differences in performance by grade ($F(3, 335) = 87.97$, $p < .001$). Planned *t*-tests revealed a significant increase in performance between junior kindergarten or kindergarten ($M = 13.71$, $SD = 7.20$) and 1st grade ($M = 24.72$, $SD = 7.93$), corresponding to the onset of literacy instruction; $t(203) = 9.65$, $p < .001$, $d = 1.45$. After the start of schooling, children showed a steady developmental increase in performance (see Figure II.1). Additional *t*-tests also revealed significant differences in children's total raw score between 1st and 2nd grade ($t(222) = 4.27$, $p < .001$, $d = 0.60$), as well as between 2nd and 3rd ($t(132) = 3.61$, $p < .001$, $d = 0.70$). All *t*-tests survive Bonferroni correction for 3 comparisons ($\alpha = .017$).

Table III.2 *Descriptive statistics and correlations between language and literacy measures*

	M	*SD*	Range	*1*	*2*	*3*	*4*	*5*	*6*	*7*
1. Age	7.39	1.06	5-9	-						
2. Vocabulary [a]	112.75	15.66	85-160	.64	-					
3. Phonological awareness [b]	11.26	2.71	3-20	.43	.42	-				
4. Single word reading [a]	110.58	16.49	66-145	.61	.52	.70	-			
5. Reading comprehension [a]	105.23	13.55	64-140	.61	.50	.65	.87	-		
6. Total ELMM (*N* = 40)	24.79	9.40	0-39	.65	.66	.59	.69	.71	-	
7. Early-acquired derivations	9.08	3.51	0-13	.61	.60	.66	.63	.66	.93	-
8. Early-acquired compounds	9.37	3.10	0-13	.56	.51	.50	.59	.60	.89	.76

Note. [a] Standard score with population mean of 100, $SD = 15$. [b] Scaled score with population mean of 10 (typical range: 8-12). Correlations are all significant at the $p < 0.001$ level (2-tailed).

We also conducted paired *t*-tests to examine age-related changes in performance on derivational affixes as compared to compound morphology (Figure III.1). For this analysis, we used 13 derived and 13 compound items, matched on age of acquisition (Kuperman et al., 2012) and frequency (Davies, 2008; MacWhinney, 2000). This choice allowed us to examine developmental differences in morphological competence with early-acquired roots and affixes. Because prior research suggests children's awareness of English lexical compounding may emerge earlier than skill with derivations (Clark, 1993), we hypothesized that our younger participants would demonstrate higher accuracy on compound items. Indeed, children's accuracy on compound items in their first year of schooling was significantly better than their accuracy on derived items. Kindergarteners and junior kindergarteners performed better on compound items (M = 38%, SD = .24) than derivational items (M = 49%, SD = .22; $t(67) = 5.42$, $p < .001$, d = 0.51). This significant difference in accuracy on compound vs. derivational items was not apparent in later grades (all ps > .05).

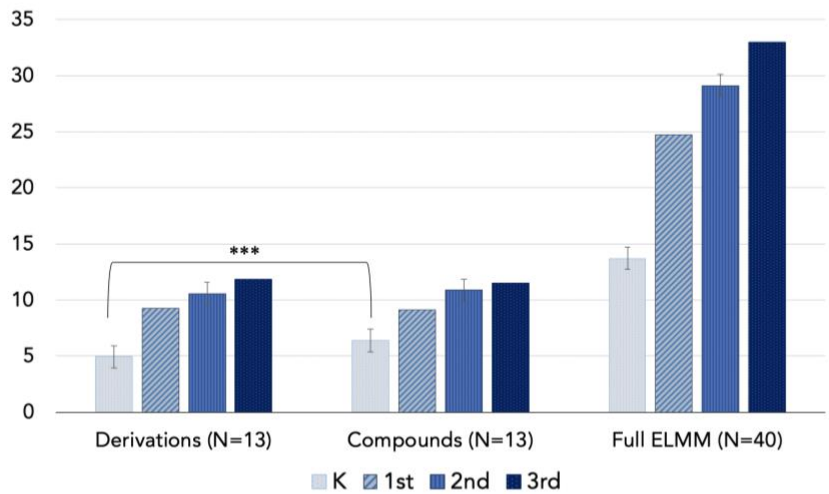


Figure III.1 *Mean number of ELMM items correct by grade*

Contribution to English Literacy

To test our hypothesis that morphological awareness is related to emerging readers' literacy skills, and the prediction that it makes an independent contribution to both single word and passage comprehension abilities, we performed two hierarchical regression analyses. Model 1 examined the relation between morphology and single word reading (see Table III.3). At step 1, we entered children's age, maternal educational attainment, and bilingual status (0 = monolingual, 1 = bilingual) as control variables. At step 2, we entered vocabulary knowledge and phonological awareness, two strong and well-established predictors of word reading. At step 3, we entered children's raw ELMM scores out of 40. Twelve participants had missing data for at least one of the included variables, leaving a test sample of $N = 318$. Results showed that morphological awareness was a significant predictor of word reading, and accounted for an additional 3.8% of the variance ($F(6, 312) = 110.7$, $p < .001$). After adding morphological awareness to the model, vocabulary knowledge was no longer significant ($p = .237$). When modeled separately at step 3, as part of a post-hoc check, both the derived ($b = 0.57$, $t = 2.44$, $p = .015$) and compound items ($b = .58$, $t = 2.43$, $p = .016$) were significant, independent predictors of word reading ($F(7, 311) = 90.34$, $p < .001$). However, because our CFA indicated that derivational and compound morphology loaded onto a single underlying factor, subsequent analyses will continue to operationalize morphological awareness using the total ELMM score.

Table III.3 *Hierarchical regression explaining single word reading*

	β	*t*	*p*	*R*	R^2	ΔR^2
Step 1				.639	.408	
Constant		-4.91	< .001			
Age	.64	14.50	< .001			
Bilingual status	.15	3.41	.001			
Maternal education	.13	2.90	.004			
Step 2				.801	.642	.234
Constant		-6.08	< .001			
Age	.32	6.86	< .001			
Bilingual status	.16	4.31	<.001			
Maternal education	.05	1.39	.166			
Vocabulary	.14	2.84	.005			
Phon. awareness	.50	12.99	< .001			
Step 3				.825	.680	.038
Constant		-3.73	<.001			
Age	.22	4.57	<.001			
Bilingual status	.19	5.51	<.001			
Maternal education	.04	1.23	.220			
Vocabulary	.06	1.19	.237			
Phon. awareness	.40	10.00	< .001			
Morph. awareness	.31	6.10	< .001			

Note. $N = 318$. Final model explains significant unique variance in single word reading, $F(6, 312) = 110.7$, $p < .001$.

In Model 2, we examined the contribution of morphological awareness to passage comprehension (see Table III.4). The final test sample was *N* = 306 because an additional 12 participants were missing passage comprehension data due to incorrect administration or difficulties in sustaining a child's attention through the long testing session. As in Model 1, we began by entering children's age, maternal educational attainment, and bilingual status as control variables. At step 2, we entered vocabulary knowledge, phonological awareness, and single word reading. Demographic variables were no longer significant predictors after the addition of children's language and literacy scores. At step 3, we entered children's raw ELMM scores. Once again, morphological awareness accounted for a small but significant amount of variance (0.8%, p = .001) in reading comprehension, above and beyond the effects of vocabulary and word reading ability.

Table III.4 *Hierarchical regression explaining reading comprehension*

	β	t	p	R	R^2	ΔR^2
Step 1				.635	.403	
Constant		-4.51	< .001			
Age	.64	14.29	< .001			
Bilingual status	.04	0.81	.421			
Maternal education	.14	2.99	.003			
Step 2				.886	.785	.382
Constant		-2.25	.025			
Age	.07	1.64	.103			
Bilingual status	-.43	-1.45	.149			
Maternal education	.00	.09	.930			
Vocabulary	.15	3.86	<.001			
Phon. awareness	.07	1.39	.059			
Single word reading	.70	15.54	<.001			
Step 3				.891	.793	.008
Constant		-1.33	.186			
Age	.03	.81	.419			
Bilingual status	-.02	-0.60	.552			
Maternal education	.00	.07	.944			
Vocabulary	.12	3.00	.003			
Phon. awareness	.05	1.28	.201			
Single word reading	.65	13.93	<.001			
Morph. awareness	.15	3.38	.001			

Note. *N* = 306. Final model explains significant unique variance in reading comprehension, $F(7, 299) = 163.67$, $p < .001$.

Finally, we conducted post hoc analyses to compare the contributions of morphological awareness to literacy outcomes in kindergarteners and 1st graders (N = 205), versus 2nd and 3rd graders (N = 135). Hierarchical regression revealed that morphological awareness made a similar unique contribution to single word reading in the younger grades ($\Delta R^2 = .045$, $\beta = .31$, $t(190) = 4.44$, $p < .001$) as in the older grades ($\Delta R^2 = .047$, $\beta = .30$, $t(127) = 3.96$, $p < .001$). However, the role of morphology in reading comprehension varied by grade. Morphological awareness made a similarly large, significant contribution to passage comprehension as to word reading in the 2nd and 3rd graders ($\Delta R^2 = .034$, $\beta = .27$, $t(124) = 3.61$, $p < .001$), but not in the younger readers ($\Delta R^2 = .005$, $\beta = .11$, $t(181) = 1.88$, $p = .062$). Full details of these post-hoc analyses are available in Appendix D, Supplementary Tables 5-8.

In sum, ELMM effectively captured developmental differences in morphological awareness in children ages 5-9, and revealed robust relationships between derivational morphology, compound morphology, and literacy skill. Together, derivational and compound morphological awareness significantly predicted both single word reading and reading comprehension when controlling for demographic variables and other language and literacy skills. The contribution of morphological awareness to single word reading was similar between kindergarten and 1st grade readers as compared to 2nd and 3rd grade readers, explaining approximately 4.5% unique variance. However, the contribution of morphological awareness to reading comprehension was driven by the older grades. Study 2A thus demonstrates a robust, concurrent relationship between morphological awareness and word reading from kindergarten through grade 3, and suggests that a similar association between morphological awareness and reading comprehension may emerge as children progress through early elementary school.

Study 2B: Bilingual Transfer Effects on Morphological Awareness and English Reading

Building on Study 2A, Study 2B examines how bilingual, cross-linguistic experiences may impact a child's morphological awareness and its relation to English literacy. Specifically, we compare Spanish-English and Chinese-English bilinguals' morphological awareness in English, and the contributions of derivational and compound morphological awareness to English literacy. These two language groups were selected because of their distinct morphological structures. In Chinese, morphemic units map directly onto characters. Each character represents a syllable, and each syllable is a morpheme, which are then combined to form compound words such as *snow+man*. Greater Chinese compound awareness in kindergarten is associated with better single word/character reading, and steeper growth trajectories in reading over time (Lin et al., 2019). In contrast to Chinese, Spanish predominantly uses derivational affixes to create multimorphemic words such as *person+al+ity*. Sensitivity to derivational morphology aids children's recognition of long, polysyllabic words, and may even serve as a mechanism for children with reading difficulties (Suárez-Coalla & Cuetos, 2013), both in Spanish and other closely-related derivationally-rich languages such as Portuguese (Oliveira et al., 2020).

Theories of bilingual transfer, namely the Linguistic Interdependence Hypothesis (Cummins, 1979) and the Interactive Bilingual Framework (Chung et al., 2019) posit that a bilingual's two languages are developmentally interconnected. When two languages are housed within a single mind or brain, they interact and influence one another at multiple levels of word processing. Indeed, some studies have revealed a direct relation between morphological awareness in a child's first language (e.g., Arabic, Spanish, or Korean), and their English word reading (Gottardo et al., 2018; Ramírez et al., 2010; Wang et al., 2009). Others have suggested that morphological awareness in a child's first language may facilitate their English literacy indirectly through English morphological awareness. Among Chinese-English bilinguals for instance, awareness of compound morphology in Chinese was found to contribute to English morphological awareness, which in turn explained variance in English reading outcomes (Lin et al., 2018; Luo et al., 2014). Similarly, among Spanish-English bilinguals, children's proficiency with Spanish derivations contributed indirectly to English reading comprehension, through English morphological awareness and vocabulary knowledge of shared cognates (Ramírez et al., 2013). In these studies, the salient morphological characteristics of children's native languages – lexical compounding in Chinese, and derivational morphology in Spanish – influenced children's developing morphological awareness in English. Bilingual experiences with structurally distinct languages may thus enhance children's sensitivity to specific morphological features, and have contrasting effects on children's literacy.

Taken together, bilingual transfer effects may manifest in a number of ways, depending on the language pairings, degree of dual language proficiency, and analytic approach. For instance, Reder et al. (2013) found that young French speakers who were learning German outperformed their monolingual French peers on compound morphology, which is more prevalent in German than in French. Notably, elementary German experience did not provide any additional benefit to bilinguals' French derivational awareness, which is more comparable across the two languages. However, experience with lexical compounding in German, a point of dissimilarity between the two languages, benefitted children's understanding of a lower-frequency feature of their L1 (Reder et al., 2013). Furthermore, bilingual transfer can manifest in the relation between morphological awareness and reading. For instance, bilingual comparisons have revealed a greater contribution of English morphology to English reading in Spanish-

English (Kremin et al., 2016) and Chinese-English (Hsu et al., 2016) bilinguals, compared to their monolingual peers. Kremin et al. (2016) compared Spanish-English bilinguals to English monolinguals and discovered that while the two groups had comparable English proficiency, bilinguals demonstrated a stronger association between morphosyntax and word reading in both of their languages. In sum, bilingual transfer may manifest both in terms of raw differences in morphological awareness skill, as well as in the strength of associations between morphological awareness and literacy outcomes.

Yet the language-specific effects of cross-linguistic experiences on morphological awareness and its relation to the emergent literacy in proficient English bilinguals remains generally unknown. In Study 2B we test the hypothesis that experience with structurally distinct home languages will have a differential impact on bilinguals' English morphological awareness and its contribution to English literacy. To test this hypothesis, we examine the effects of cross-linguistic experiences with typologically distinct morphologies, Spanish and Chinese, on English literacy. First, we ask whether children's morphological awareness varies as a function of their language background. Specifically, do bilingual children demonstrate greater awareness of the morphemic features that are characteristic of their home language (derivational morphology for Spanish-English bilinguals, and lexical compounding for Chinese-English bilinguals)? Second, does bilingual experience with specific morphemic structures influence the roles of derivational and compound morphological awareness in English reading? Guided by theories of bilingual transfer (Chung et al., 2019), we hypothesize that bilinguals will rely more heavily on the morphological forms that are shared between English and their heritage language. However, it is also possible that bilinguals' growing awareness of less familiar, lower-frequency morphological structures may help to explain differences in their English reading outcomes. Finally, we may find no differences attributable to bilingual experiences, as English reading might place overwhelmingly language-specific demands on both bilingual and monolingual learners.

Method

The overarching goal of Study 2B was to examine how bilingual experiences with structurally distinct languages might influence English morphological awareness and its contribution to word reading and passage comprehension. To examine specific cross-linguistic differences, we first limited our inquiry to children who were heritage speakers of Spanish or Chinese and had not been exposed to additional languages.

Sixty-nine Spanish-English bilinguals and 80 Chinese-English bilinguals met these criteria. These bilingual participants all had at least one parent or primary caregiver who was a native speaker of either Spanish or Chinese, and had been exposed to their heritage language since birth. Nearly 18% of these children attended language immersion public schools (8 Spanish-English immersion, and 16 Chinese-English immersion), while the remaining participants attended English-only general education programs. An additional 34% received some formal literacy instruction in their heritage language through extracurricular activities, such as a Saturday language school (18 Spanish, and 28 Chinese). An additional 27 Spanish-speaking parents and 2 Chinese-speaking parents reported that they were teaching their child to read at home in the absence of formal heritage language literacy instruction. Notably, all bilingual children were all fluent in English, with mean vocabulary standard scores of 106.87 (SD = 14.69), and had age-appropriate home language vocabulary knowledge, as demonstrated by their standard scores (Spanish M = 108.60, SD = 16.20; Chinese M = 95.90, SD = 17.39). Bilinguals thus had relatively high and balanced dual-language proficiency.

We then identified a subsample of English monolinguals with similar English language and literacy skill to our bilingual participants, and no sustained exposure to other languages. In our full sample in Study 2A, we observed higher standard scores of English vocabulary among monolinguals (M = 118.51, SD = 14.35) than bilinguals (M = 106.67 SD = 14.69; $t(333) = 7.47$, $p < .001$, $d = 0.82$). To disentangle effects due to language background versus differences in English vocabulary knowledge (Hammer et al., 2014), we used the MatchIt package in R (Ho et al., 2011) to create three groups of English monolinguals, Spanish-English bilinguals, and Chinese-English bilinguals with similar covariate distributions of their English vocabulary and English word reading ability. The English monolingual and Chinese-English bilingual groups each had 69 participants, matched to the 69 eligible Spanish-English bilinguals, resulting in a total sample of N = 207.

Using these matched groups, we then examined bilingual transfer in two ways. First, we compared differences in bilingual children's awareness of English morphological structures that were shared across their two languages (e.g., derivations for Spanish-English bilinguals, and compounds for Chinese-English bilinguals) versus those that were dissimilar. Second, we examined how bilingual and cross-linguistic experiences with typologically distinct morphologies might influence the relation between English morphological awareness and English literacy.

Results

Descriptive Analysis

Table III.5 provides descriptive statistics of raw achievement scores across the three groups, and Table III.6 provides the intercorrelations between language and literacy variables for each language group. To confirm that our three groups were well-matched, we conducted a one-way ANOVA which revealed no significant group differences in English vocabulary, phonological awareness, word reading, reading comprehension or morphological awareness. There were significant differences between the groups in age ($F(2, 204) = 5.27$, $p = .006$) and maternal education ($F(2,195) = 6.02$, $p = .003$). Nevertheless, these subsamples of English monolinguals, Spanish-English bilinguals, and Chinese-English bilinguals performed equivalently on all measures of raw English language and literacy skill.

Table III.5 *Descriptive statistics and ANOVA testing for differences in English language and literacy ability across language groups*

	English monolinguals		Spanish-English bilinguals		Chinese-English bilinguals			
	M	*SD*	*M*	*SD*	*M*	*SD*	*F*	*p*
Age	7.38	1.05	7.64	1.03	7.04	1.19	5.27	.006
Maternal education [a]	9.04	1.67	8.21	2.26	9.39	2.03	6.02	.003
English vocabulary [b]	147.16	17.64	142.30	21.33	139.74	25.29	2.19	.114
Phonological awareness [b]	22.88	6.51	22.71	7.72	22.32	6.86	0.11	.893
Morphological awareness [b]	19.51	5.65	17.59	6.19	17.30	6.70	2.58	.079
Single word reading [b]	46.51	13.56	47.43	14.11	47.52	13.85	0.11	.892
Reading comprehension [b]	25.79	7.61	24.08	7.25	25.67	7.21	1.13	.326
Spanish/Chinese vocabulary [c]	-	-	108.60	16.20	95.90	17.39	2.89	.091

Note. [a] Educational attainment scale: 8 = Completed bachelor's degree; 9 = Some graduate school; 10 = Completed master's degree. [b] Raw score on subset of 26 items. [c] Standard scores but normed on different populations.

Table III.6 *Intercorrelations between literacy variables by language group*

	1	*2*	*3*	*4*	*5*
English monolinguals (*n* = 69)					
1. Vocabulary	-				
2. Phonological awareness	.50	-			
3. Morphological awareness	.66	.65	-		
4. Single word reading	.74	.62	.79	-	
5. Reading comprehension	.71	.71	.78	.91	-
Spanish-English bilinguals (*n* = 69)					
1. Vocabulary	-				
2. Phonological awareness	.47	-			
3. Morphological awareness	.65	.63	-		
4. Single word reading	.58	.80	.70	-	

5. Reading comprehension	.72	.67	.72	.85	-
Chinese-English bilinguals (*n* = 69)					
1. Vocabulary	-				
2. Phonological awareness	.51	-			
3. Morphological awareness	.69	.55	-		
4. Single word reading	.74	.74	.76	-	
5. Reading comprehension	.72	.64	.74	.86	-

Note. All correlations are significant at the $p < 0.001$ level (2-tailed).

Performance on Derived vs. Compound Morphology

The first aim of Study 2B was to examine how children's bilingual experiences with distinct morphological structures might influence their morphological awareness in English. Guided by theories of bilingual transfer, we compared Spanish-English and Chinese-English bilinguals' performance on derivational vs. compound items of the ELMM. This analysis specifically considered the subset of 26 early acquired items, which included 13 derived and 13 compound items with similar frequency and age of acquisition. We hypothesized that bilingualism would alter a child's general linguistic system, lexicon, and sensitivity to certain grain sizes, thereby influencing the reading process in English. Specifically, we predicted that Spanish-English bilingual children would show advantages in English derivational morphology, while Chinese-English bilingual children would show advantages in English compound morphology.

We conducted two independent sample *t*-tests to compare Spanish- and Chinese-English bilinguals' proficiency with derivational and compound morphology. For derivations, Spanish-English bilinguals responded correctly to an average of 8.35 out of 13 items (*SD* = 3.65), while Chinese-English bilinguals responded correctly to an average of 8.51 out of 13 items (*SD* = 3.77). For compounds, Spanish-English bilinguals' mean accuracy was 9.25 (*SD* = 2.98) while Chinese-English bilinguals' mean accuracy was 8.81 (*SD* = 3.40). *T*-tests revealed no significant differences in either derivational ($t(136) = -.25$, $p = .801$) or compound morphological awareness ($t(136) = .80$, $p = .425$) across bilingual language groups. In other words, our findings did not support the hypothesis that children's awareness of compound and derivational morphology would vary as a function of their bilingual background.

Contributions of Derivational vs. Compound Awareness to English Literacy

The second aim of Study 2B was to examine possible bilingual differences in the relation between English morphological awareness and English literacy. Might bilingual experience with structurally distinct languages influence the roles of derivational and compound morphological awareness in English reading? We hypothesized that compound and derivational morphological awareness would differentially contribute to children's English reading as a function of their bilingual language backgrounds.

In parallel to Study 2A, we conducted multiple regression analyses to predict variance in single word reading and reading comprehension. Both models included language group (LG) as a factor with three levels (English monolingual, Spanish-English bilingual or Chinese-English bilingual), children's ELMM score on derivations, and their score on compounds. Age, maternal education, and English vocabulary were included as covariates. All predictors were *z*-scored, and interaction terms were computed using the language group factor and the *z*-scored Derivations and Compounds variables. Regression results are presented in Tables 7 and 8, using both Spanish-English and Chinese-English bilinguals as a reference group.

In our first model (Table III.7), we predicted children's English word reading from their age, maternal education, English vocabulary knowledge, language group, derivational awareness, compound awareness, and the interactions between the language group factor and the two types of morphological awareness. The covariates of no interest (age, maternal education, and English vocabulary) were all significant predictors of word reading. There was a significant effect of language group, in which both Spanish bilinguals (*b* = 0.25, *t* = 2.37, *p* = .019) and Chinese bilinguals (*b* = 0.38, *t* = 3.77, *p* < .001) differed significantly from the English monolinguals, but not from one another. Furthermore, findings revealed significant main effects of derivational awareness and compound awareness, as well as significant interactions between language group and derivational vs. compound morphology. These results are presented in Table III.7.

Table III.7 *Regression explaining word reading from morphology X language group interaction*

Reference group: Spanish bilinguals					Reference group: Chinese bilinguals				
	β	*t*	*p*			β	*t*	*p*	
Constant	-1.75	-3.85	<.001	***	Constant	-1.62	-3.76	<.001	***
Age	0.24	4.05	<.001	***	Age	0.24	4.05	<.001	***
Maternal education	0.13	2.87	.005	**	Maternal education	0.13	2.87	.005	**
Vocabulary	0.19	2.86	.005	**	Vocabulary	0.19	2.86	.005	**
LG: Chinese	0.13	1.22	.224		LG: Spanish	-0.24	-1.22	.224	
LG: English	-0.25	-2.57	.019	*	LG: English	-0.38	-3.77	<.001	***
Derivations	-0.01	-0.10	.918		Derivations	0.37	3.24	.001	***
Compounds	0.48	4.14	<.001	***	Compounds	0.07	0.71	.481	
Chinese * Derivations	0.39	2.55	.011	*	Spanish * Derivations	-0.39	-2.55	.011	*
English * Derivations	0.55	3.53	.001	***	English * Derivations	0.17	1.08	.282	
Chinese * Compounds	-0.42	-2.70	.008	**	Spanish * Compounds	0.42	2.70	.008	**
English * Compounds	-0.39	-2.47	.014	*	English * Compounds	0.03	0.20	.846	

Note. LG = Language Group. $F(11, 191) = 38.27$, $p < .001$, adjusted $R^2 = 0.67$.

To decompose the significant interactions between language group and derivational vs. compound morphology (Figure III.2), we examined the simple slopes of the morphological awareness variables across the bilingual groups. For Spanish-English bilinguals, compound awareness was significantly associated with English word reading (*b* = .48, *t* = 4.14, *p* < .001), while derivational morphological awareness was not (*b* = -.01, *t* = -0.10, *p* = .918). In contrast, for Chinese-English bilinguals, derivational morphological awareness was significantly associated with word reading (*b* = .37, *t* = 3.24, *p* = .001) while compound awareness was not (*b* = .07, *t* = 0.71, *p* = .481). In other words, only compound morphology explained unique variance in Spanish-English bilinguals' word reading, while only derivational morphology explained unique variance in Chinese-English bilinguals' word reading. The roles of derivational and compound morphology in monolingual English readers were similar to the Chinese-English bilinguals. English monolinguals had the steepest slope for derivational awareness (b = .54, t = 4.69, p < .001), although it was not significantly different from the Chinese-English bilinguals, while compound awareness was not significant (b = .10, t = 0.90, p = .369).

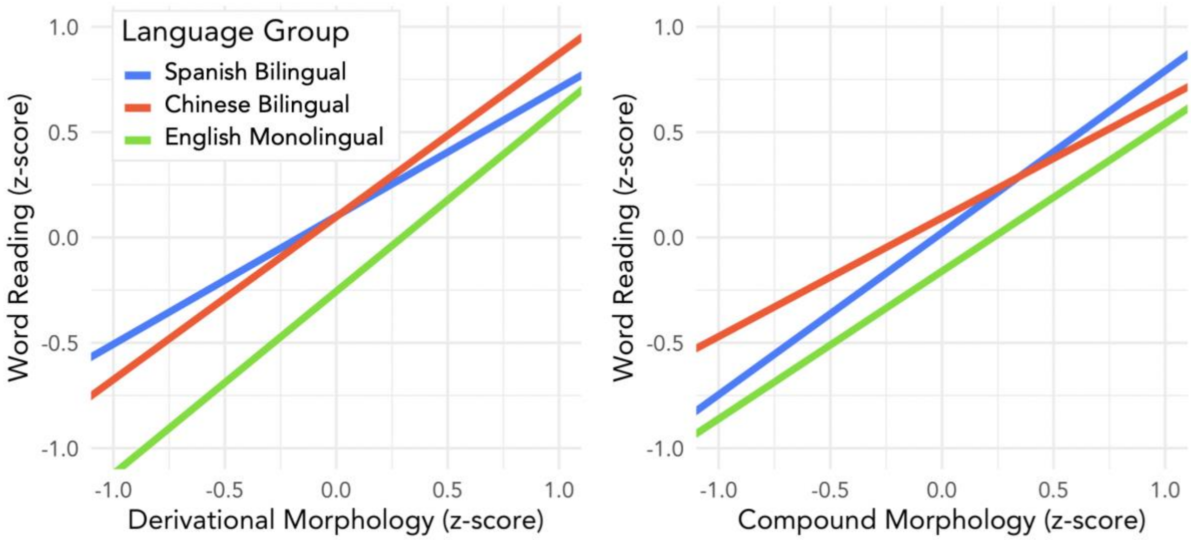


Figure III.2 *Interaction between morphological awareness item type and language group*

Finally, we examined the contribution of derivational and compound morphological awareness to reading comprehension. Like the first model, we included language group, derivational awareness, compound awareness, and the interactions between the language group factor and the two types of morphological awareness. Age, maternal education, English vocabulary, and English word reading were all included as covariates, mirroring the second regression analysis in Study 2A. Results reveal significant effects of English vocabulary, English single word reading, and language group on passage comprehension (R^2 = .76, F(11, 187) = 57.40, p < .001). Neither awareness of derivational morphology nor compound morphology were significant predictors (see Table III.8). This null finding suggests that morphological awareness may primarily influence literacy through single word reading, as demonstrated by prior work (Deacon et al., 2014).

To further explore this interpretation, we conducted an exploratory post-hoc analysis in which we removed single word reading from the model. When word reading was not included as a predictor, we once again observed significant effects of morphological awareness on reading comprehension (compounds for Spanish-English bilinguals: $b = .34$, $p = .007$; derivations for Chinese-English bilinguals: $b = .31$, $p = .007$; see Appendix D, Supplementary Table D.9). Taken together, these results strengthen the interpretation that morphological awareness influences literacy directly through single word reading, and that single word reading in turn impacts reading comprehension.

Table III.8 *Post-hoc regression explaining reading comprehension from morphology X language group interaction*

Reference group: Spanish bilinguals					Reference group: Chinese bilinguals				
	β	*t*	*p*			β	*t*	*p*	
Constant	-0.44	-1.15	.252		Constant				
Age	0.04	0.77	.440		Age	0.04	0.77	.440	
Maternal education	-0.01	-0.15	.885		Maternal education	-0.01	-0.15	.885	
Vocabulary	0.16	3.10	.002	**	Vocabulary	0.16	3.10	.002	**
Word reading	0.62	10.50	<.001	***	Word reading	0.62	10.50	<.001	***
LG: Chinese	0.22	2.53	.012	*	LG: Spanish	-0.22	2.53	.012	*
LG: English	0.19	2.14	.034	*	LG: English	-0.03	-0.38	.706	
Derivations	0.15	1.67	.096		Derivations	0.10	1.08	.282	
Compounds	-0.01	-0.08	.933		Compounds	0.01	0.11	.910	
Chinese * Derivations	-0.05	-0.39	.696		Spanish * Derivations	0.05	0.39	.696	
English * Derivations	0.09	0.65	.514		English * Derivations	0.12	1.11	.271	
Chinese * Compounds	0.02	0.14	.892		Spanish * Compounds	-0.02	-0.14	.892	
English * Compounds	0.01	0.10	.924		English * Compounds	-0.01	-0.04	.965	

Note. LG = Language Group. $F(12, 184) = 64.68$, $p < .001$, adjusted $R^2 = 0.80$.

Discussion

The overarching goal of this manuscript was to examine the role of derivational and compound morphological awareness in English literacy in monolingual and bilingual children, ages 5-9. Study 2A revealed a robust contribution of derivational and compound morphological awareness to word reading, as well as a more modest contribution of morphological awareness to reading comprehension. Study 2B revealed principled cross-linguistic influences of bilingualism on the relationship between children's morphological awareness and learning to read: bilinguals' proficiency with the type of morphology that was *less* characteristic of their home language explained greater variance in their English literacy. The present findings advance theoretical perspectives on literacy in monolingual and bilingual learners by clarifying the association between morphological awareness and early English literacy skill, as well as the cross-linguistic bilingual effects on this association.

Assessing Morphological Awareness

Leveraging the body of knowledge on morphology development, we modified an existing measure to be maximally sensitive to children's emerging awareness of lexical morphology between kindergarten and 3rd grade. Our Early Lexical Morphology Measure (ELMM) built upon the well-established Decomposition (Carlisle, 2000) or Extract the Base (Goodwin et al., 2011) task model (e.g., *Playful. Let's go outside and* ___ [play]). To ensure accessibility for our youngest participants, we modified morphemic, sentential, and lexical features of the task. Most notably, we included lexical compounding, an early-emerging component of English morphological awareness. We additionally modified derivational items from the Extract the Base measure (Goodwin et al., 2011) such that all items were based on child-friendly root words (e.g., *noise, color* as opposed to *reduce, proceed*), and embedded these words at the end of short sentences to reduce working memory load. ELMM performance meaningfully captured variability in morphological competence across a wide age range: there was no floor effect in 5-

year-old kindergarteners, and no ceiling effect in 9-year-old 3rd graders. To our knowledge, this is the first measure of lexical morphology appropriate across this age range. This represents an important methodological advancement in the field, as it captures the critical transition from "learning to read" to "reading to learn" in elementary school.

ELMM not only captured a steady increase in morphological awareness from kindergarten through 3rd grade; it also revealed developmental differences in children's faculty with compound versus derivational morphology more specifically. Notably, structural equation modeling indicated that children's accuracy on compound and derived items was best explained by a single underlying factor, rather than as two unique morphology constructs. However, in the first year of schooling, children were significantly better at extracting root morphemes from compound words (e.g., *rain* from *rainbow*), than from derived words (e.g., *quick* from *quickly*). This finding is closely aligned with recent work suggesting that young German readers are sensitive to compound lexical structure earlier than derivational prefixes or suffixes (Hasenäcker et al., 2017). By 1st grade, children in our study were able to extract root morphemes from derived and compound words equally well, and with evidence of further improvement in 2nd and 3rd grade. This dramatic change in derivational morphological awareness between kindergarten and 1st grade may be related to the documented association between derivational vocabulary knowledge and schooling experience (Anglin, 1993). This finding enhances our understanding of the developmental trajectory of morphological awareness, and reinforces the value of assessing compound morphology at the onset of schooling. By using early-acquired root words, a broad range of morphological constructions, and compound morphology in addition to derivations, we gain a clearer picture of children's morphological awareness and the nature of its contribution to early reading development.

Morphological Awareness and Early English Literacy

The main goal of Study 2A was to investigate the concurrent association between morphological awareness and early literacy in a diverse group of 5-9-year-old children. Guided by the Reading Systems Framework (Perfetti & Stafura, 2014), we predicted that morphological awareness would contribute to both single word reading and reading comprehension in young readers.

Single Word Reading

At the single word level, both compound and derivational morphological awareness explained significant unique variance in children's word reading, above and beyond phonological awareness, vocabulary, and demographic variables. Importantly, this finding was consistent across grades and levels of reading ability: the ELMM task explained an additional 4.5% unique variance in word reading for children in kindergarten and 1st grade, as compared to 4.7% unique variance for the older 2nd-3rd graders. These findings reveal a robust contribution of morphological awareness to early English word reading at the onset of schooling as well as in slightly more advanced readers.

This result is closely aligned with both the Reading Systems Framework (Perfetti & Stafura, 2014) as well as Psycholinguistic Grain Size Theory (Ziegler & Goswami, 2005). First, the Reading Systems Framework posits that as morphology is integral to each word, it should play an important role in single word identification. Second, Psycholinguistic Grain Size Theory suggests that due to the opacity of English orthography and inconsistent sound-to-print mapping, English readers may need to rely on a larger grain size (e.g., morphemes rather than single phonemes) to identify words. We find strong evidence in support of both of these theoretical perspectives, revealing that morphological awareness contributes to single word reading, including in kindergarten and 1st grade beginning readers. This finding meaningfully extends prior work that identified an existing but less consistent association between morphology and early literacy skill (Apel et al., 2013; Law & Ghesquière, 2017).

Reading Comprehension

At the level of connected text, morphological awareness (operationalized in terms of both compound and derivational awareness) explained a small but significant amount of variance in children's reading comprehension, above and beyond the effects of single word reading, phonological awareness, vocabulary, and demographic variables. This finding provides further support for the Reading Systems Framework (Perfetti & Stafura, 2014), which suggests a dual contribution of morphological awareness to literacy at both the single word and passage level. It is important to note that the effect of morphological awareness on passage comprehension is small (0.8% unique variance explained). This finding is logical in light of prior work suggesting that word reading (Deacon et al., 2014) or morphological decoding (Levesque et al., 2017) may partially mediate the relationship between morphological awareness and reading comprehension. This small effect may also point to the budding emergence of this association, as others have suggested that the contribution of morphology to reading comprehension may increase with age and reading proficiency (Deacon & Kirby, 2004; Singson et al., 2000).

Furthermore, the dividing line between word identification and reading comprehension may not be entirely clear in the earliest stages of reading development (Lonigan & Burgess, 2017). Indeed, post hoc analyses suggest an important effect of grade level. Among 2nd and 3rd grade readers, morphological awareness explained 3.4% of variability in reading comprehension, while the contribution of morphological awareness to kindergarten and 1st grade reading comprehension was not significant. In other words, the significant association between morphological awareness and reading comprehension was driven by our older, more proficient readers. Our findings thus further the idea of developmental continuity in the role of morphological awareness across the elementary school years.

Together, our findings for single word reading and reading comprehension further our understanding of the role of morphological awareness in early English reading. They further align our understanding of morphology in English literacy acquisition with our growing knowledge of reading development across languages. English is notoriously phonologically opaque, and theoretical models have suggested that English readers only begin to rely on larger morphemic units once they are able to successfully decode words (Ehri, 2014). Yet cross-linguistic research has demonstrated the importance of morphological awareness for early reading across a wide range of languages and orthographies including Chinese (Pan et al., 2016), French (Colé et al., 2018), Greek (Manolitsis et al., 2017), and both Japanese Kanji and Hiragana (Muroya et al., 2017). We contribute to this cross-linguistic evidence by demonstrating that English-speaking children's morphological awareness is a significant contributor to their concurrent word reading skill, even in kindergarten. These findings logically situate English literacy acquisition alongside reading development across languages and orthographies.

Morphological Awareness and English Literacy in Spanish- and Chinese-English Bilinguals

Performance on Derivational Versus Compound Morphology

First, regarding children's task performance, we predicted that bilingual experiences with derivationally-rich Spanish would enhance Spanish-English bilinguals' performance with English derivations (e.g., extracting *argue* from *argument*), compared to Chinese-English bilinguals (Ramírez et al., 2011). Conversely, we predicted that experience with the compound structure of Chinese would enhance children's performance with of English lexical compounding (e.g., extracting *walk* from *sidewalk*). Interestingly, independent sample *t*-tests revealed no differences between Spanish-English and Chinese-English bilinguals' accuracy on derived or compound items. This null finding is likely the result of our experimental approach and participant groups. Prior research has revealed differences in compound versus derivational morphology in Spanish- and Chinese-speakers who were learning English (Ramírez et al., 2011); in contrast, our participants had high dual-language proficiency, including age-appropriate English vocabulary and literacy scores. Differences in English morphological awareness may therefore exist between bilingual groups with lower English proficiency levels, but these were not observed in our high proficiency speakers.

Bilingual Effects on English Word Reading

Second, we predicted that bilingual experience may have a differential effect on how compound and derivational morphological awareness contribute to English reading for Spanish-English and Chinese-English bilingual learners. We predicted that Spanish-English bilinguals would show a stronger relation between derivational morphology and word reading, while Chinese-English bilinguals would demonstrate a stronger relation between compound morphology and word reading.

Indeed, multiple regression revealed significant interactions between morphological item type (derivations vs. compounds) and language group (monolingual vs. Spanish-English bilingual vs. Chinese-English bilingual), supporting our overarching hypothesis that experience with structurally distinct languages would alter the relation between morphology and English word reading. Yet the direction of these bilingual effects was contrary to our prediction.

Awareness of compound morphology explained significant variance in Spanish-English bilinguals' word reading, while derivational awareness did not. Conversely, awareness of derivational morphology explained significant variance in Chinese-English bilinguals' word reading, while compound awareness did not. In other words, differences in English word reading skill among bilingual children was best explained by variation in the type of morphology that was dissimilar or *less* characteristic of a child's home language.

These findings are consistent with a usage-based hypothesis of language acquisition. The usage-based framework suggests that successful language learning requires that a learner has encountered sufficient examples of a specific linguistic form to be able to make broader generalizations (Ellis, 2002). While a beginning learner may rely heavily on aspects of a new language that can be transferred from their L1, a more advanced learner requires explicit instruction in the unique aspects of the second language that cannot be transferred. It is experience with less frequent structures – for instance, the structures that are unique to a single language and not shared across a bilingual's two languages – that are necessary to drive additional growth. For the highly proficient bilinguals in our present study, successful English reading is most dependent children's proficiency with the features of English that cannot be gleaned from their home language. These findings reinforce the idea that explicit morphological instruction may benefit young learners, and provide preliminary insight into how this instruction could be individualized across diverse students. Teachers and clinicians may want to consider the linguistic features of students' home languages, and target instruction towards the specific features of English that students are unable to transfer from their L1.

In sum, our findings reveal linguistically principled bilingual effects on word reading in high proficiency bilinguals, and suggest that greater familiarity with linguistic features that are dissimilar across the children's two languages may bolster reading success. These findings both extend and complicate theories of bilingual language transfer (Chung et al., 2019). For bilingual children who are still acquiring their language of schooling (e.g., Ramírez et al., 2011), their established proficiency in L1 should contribute to and scaffold their emerging proficiency in L2. For bilinguals who are highly proficient in both of their languages, the cognitive processes underlying reading may look different. By studying high-proficiency bilinguals, we gain additional insight into the language-specific effects of contrasting bilingual experiences on morphology and its contribution to English literacy. The observed bilingual differences are thus consistent with the idea that bilinguals' two languages interact to influence literacy (Linguistic Interdependence Hypothesis; Cummins, 1979), as well as the notion that bilingual transfer effects may be influenced by children's relative language proficiency, and manifest in a number of ways (Interactive Transfer Framework; Chung et al., 2019).

Bilingual Effects on English Reading Comprehension

Finally, we conducted two post-hoc analyses to examine whether children's bilingual language backgrounds might moderate the relation between morphological awareness and children's English reading comprehension. When English single word reading was included in the regression model (akin to the regression analyses in Study 2A), we observed a main effect of language group, but no effect of derivational or compound morphological awareness. When word reading was not included as a covariate, derivational and compound morphological awareness re-emerged as significant predictors. Again, compound awareness was a significant predictor of reading comprehension for Spanish-English bilinguals, while derivational awareness was a significant predictor of reading comprehension for Chinese-English bilinguals.

These exploratory analyses suggest that morphological awareness primarily contributes to English literacy through word reading. Indeed, prior work has suggested that morphological awareness has a direct effect on single word reading, and an indirect effect on reading comprehension through word reading (Deacon et al., 2014). Our findings thus extend and build upon this prior work in support of the Reading Systems Framework (Perfetti & Stafura, 2014), which posits that morphological awareness plays multiple roles in the reading system. We find that bilingual language experience, which may be conceptualized as a part of the general linguistic system, has a direct effect on reading comprehension. In contrast, the specific effects of derivational and compound morphological awareness, which are moderated by language experience, may operate primarily at the single-word level.

Limitations

This manuscript has several caveats. Although our sample is ethnically, linguistically and geographically diverse, participants come from families of predominantly middle-to-high socioeconomic and education status. On one hand, this is a particularly important limitation given that bilingual learners in the United States often grow up in homes with a lower socioeconomic status, which has a well-documented impact on language development (Hoff et al., 2012). On the other hand, this unique sample may serve to dissociate bilingual experiences from the confound of SES, providing insight into cross-linguistic influences on literacy. Our inquiry is also limited to one morphological awareness task, and lacks an explicit measure of multimorphemic word reading. Although we examined multiple types of morphemic constructions through ELMM in conjunction with standardized literacy assessments, future research may benefit from careful consideration of multimorphemic word or pseudoword reading tasks (e.g. Hasenaäcker, Schröter & Schroeder, 2017). Nevertheless, our findings suggest a meaningful relationship between morphological awareness in spoken language, reading single words, and understanding passages of connected text.

Conclusion

This manuscript offers both theoretical and practical implications for understanding the role of morphology in reading development. First, our findings advance current theoretical perspectives on English reading acquisition by demonstrating that children's morphological awareness contributes to their literacy achievement as early as age 5. Our data suggest an early-emerging association between children's morphological awareness and literacy acquisition that is influenced by children's English, as well as cross-linguistic experiences. At the practical level, these findings reinforce the idea that morphology and morphological training may benefit young learners, even in the early stages of literacy acquisition (Goodwin & Ahn, 2013; Lyster et al., 2016). Furthermore, instructors may need to consider not only children's English language proficiency but also the heterogeneity in their linguistic backgrounds, as bilingual learners might find it especially beneficial to study the morphemic features that are not shared with their home language. In sum, this manuscript broadens our understanding of reading development in English and multilingual learners, and puts forth a practical tool for studying morphological development in young children from linguistically-diverse backgrounds.

CHAPTER IV. Morphological Processing in Typical and Impaired Readers

The goal of reading is to comprehend meaning from text. However, for children with dyslexia, deficits in single word reading may impede the ability to extract units of meaning, leading to impaired reading comprehension. Over the past several decades, we have gained substantial insight into the neurocognitive differences underlying dyslexia, most notably in phonological processing. However, much less is known about the role of morphological awareness, or children's sensitivity to units of meaning, in readers with dyslexia. Accordingly, the present study investigates the role of morphological awareness both behaviorally and in the brain of young learners across a wide range of reading ability. We ask two main questions. First, how does morphological awareness contribute to reading comprehension in children with and without reading impairment? Second, how is the brain basis of morphological processing associated with skilled reading comprehension?

In typical readers, morphological awareness, or sensitivity to units of meaning, makes a critical contribution to literacy. Morphological awareness may be understood along developmental continuum from implicit awareness to an explicit understanding of morphology over the course of schooling (Carlisle, 2004). Prior to formal literacy instruction, children recognize morphemic regularities and can manipulate morphemes in speech (Berko, 1958). This tacit or implicit awareness deepens children's word knowledge, connecting mental representations of sound, print, and meaning, and facilitating easier word recognition (Nagy et al., 2014). In more mature readers, tacit morphological awareness may act as the foundational knowledge that supports more explicit literacy strategies such as morphological analysis and decoding (Levesque et al., 2020). The present study examines children's implicit morphological processing and its relation to reading comprehension skill.

Theoretical perspectives (Levesque et al., 2020; Perfetti & Stafura, 2014) suggest that morphology makes both direct and indirect contributions to reading. First, every word is comprised of one or more morphemes, such as in *bat*, *snow+man,* or *creat+iv+ity.* Morphological awareness thus contributes directly to single word recognition by providing information about word segmentation, pronunciation, and meaning. Indeed, morphology may be seen as a "binding agent" that connects representations of sound, meaning, and print together, thereby strengthening mental representations of words themselves (Kirby & Bowers, 2017; Perfetti, 2007). Second, morphology is also a component of the general linguistic system, and contributes directly to multiple levels of word and sentence-level language competence. In support of this framework, a growing body of evidence has revealed both direct and indirect associations between morphological awareness and reading comprehension (e.g., Deacon et al., 2014; Gilbert et al., 2014; James et al., 2021; Kieffer & Lesaux, 2012; Levesque et al., 2017; Nagy et al., 2006). Within the Simple View of Reading (SVR) framework, which posits that reading comprehension builds upon single word decoding and broader language proficiency (Hoover & Gough, 1990), morphological awareness may contribute to both of these elements.

Of particular importance for reading comprehension in English is derivational morphology, which involves adding derived affixes to root morphemes to change the meaning or part of speech, as in *beauti+ful+ly* or *in+decis+ion.* As children progress through school, they encounter an increasing number of complex words in academic texts, over half of which are multimorphemic derived words (Nagy & Anderson, 1984). In contrast to analyzing root morphemes, derivational affixes are more semantically abstract, and may be more analytically demanding for readers. Derivational morphological awareness has been shown to contribute directly to 6th graders' reading comprehension, as well as indirectly through their vocabulary knowledge and word reading skill (Kieffer & Box, 2013). Furthermore, two separate studies found that children with poor reading comprehension skills underperform on derived items of a word analogy task (*paint : painter :: bake :* __) as compared to their word-reading matched peers with average reading comprehension skill (MacKay et al., 2017; Tong et al., 2011). Derivational morphological awareness is thus a promising area of inquiry, and may hold a valuable key to better understanding literacy acquisition and reading comprehension difficulties. Yet despite its importance for successful reading, the role of morphological awareness in impaired reading, as well as the neurocognitive mechanisms that underlie morphological processing in both typical reading and dyslexia, remain largely unexplored.

Importantly, little is known about the role of morphological awareness in children who struggle to read. Behavioral evidence suggests that children with dyslexia, a reading impairment associated with phonological deficits and word reading difficulty, consistently perform lower on tasks of morphological awareness as compared to same-aged peers (Casalis et al., 2004; Kearns et al., 2016). For instance, retrospective analysis of 2nd graders with reading difficulties revealed that those children also had deficits in both phonological and morphological awareness in kindergarten, at the onset of learning to read (Law & Ghesquière, 2017). Similarly, preschoolers at family risk for developing dyslexia perform significantly lower on tasks of morphological awareness compared to an age-matched group of children with low risk for dyslexia (Law et al., 2017).

However, there are conflicting perspectives as to the etiology of these morphological difficulties. On one hand, these differences in morphological awareness may be a downstream consequence of impaired phonological awareness. In support of this perspective, Law and colleagues (2017) found that group differences in morphological awareness subside after controlling for phonological awareness. Similarly, Tsesmeli and Seymour (2006) found that adolescents with dyslexia underperformed on a morphological awareness task compared to age-matched controls but not reading-matched controls, suggesting that difficulties with morphological segmentation may simply be a cascading result of poor reading performance rather than a unique deficit (Tsesmeli & Seymour, 2006). On the other hand, it is possible that poor morphological awareness may be distinct from poor phonological processing. In support of this perspective, children with unexpectedly poor comprehension skill despite adequate word reading ability demonstrate a specific morphological deficit independent of phonological difficulties (MacKay et al., 2017; Tong et al., 2011, 2013). Furthermore, a growing body of work suggests that morphological awareness contributes significantly to reading after controlling for phonological awareness, indicating that morphological processing is at least partially distinct from phonological processing (Carlisle & Nomanbhoy, 1993; Deacon & Kirby, 2004; Desrochers et al., 2018).

Neuroimaging research has the potential to shed light on these conflicting perspectives regarding morphological awareness in reading (dis)ability. However, few studies have examined the neural correlates of lexical morphology in impaired developing readers. In a recent study of Finnish preschoolers with and without family risk of dyslexia, Louleli and colleagues (2020) asked participants to listen to sentences with correct and incorrect morphological derivations. This study revealed no significant differences between the control group and high risk group, raising the possibilities that dyslexia-related differences in morphological processing may not be present in the auditory modality, or prior to reading instruction (Louleli et al., 2020). In contrast, two known studies of older children with dyslexia have revealed hypo-activation during morphological processing (Aylward et al., 2003; Richards et al., 2006), much like the well-documented hypo-activation during phonological processing. In both studies, children read two words and were asked to decide if those were related in meaning (*builder-build* vs. *corner-corn*) during fMRI neuroimaging. Aylward and colleagues (2003) found that children with dyslexia exhibited reduced activation in the same frontal, parietal-temporal, and occipital regions previously associated with phonological impairments (Norton et al., 2015). Richards and colleagues (2006) also found that brain activation in children with dyslexia was more bilateral whereas in typical readers it was more left-lateralized. However, because the tasks required word reading, the question remains as to the extent to which these findings were driven by lower word reading abilities in children with dyslexia.

Studying morphological awareness in spoken language, which precedes and predicts successful reading, may help to shed light on the brain basis of morphology in typical and atypical readers independent of word reading skill. The dual-route model of language processing suggests the involvement of two neurocognitive pathways: a dorsal pathway, which is primarily involved in phonological processing, and a ventral pathway engaged in efficient sound-to-meaning mapping (Hickok & Poeppel, 2007). Similarly, word reading relies on a dorsal circuit associated with phonological analysis and integrating phonological and orthographic information, as well as a ventral circuit associated with efficient mapping between orthography and semantics (Pugh et al., 2000; Shuai et al., 2019). Of particular interest to the current study is the relative contributions of phonological versus semantic mechanisms in morphological processing, and the extent to which each is associated with reading comprehension.

The aim of the present study was to examine the behavioral and neurobiological correlates of morphological awareness, and their relation to reading comprehension skill, in children with and without reading impairment. First, guided by the SVR model (Hoover & Gough, 1990), we ask: Does morphological awareness play a role in reading comprehension, above and beyond the contributions of vocabulary knowledge and word decoding skill? Second, what are the neural mechanisms underlying sensitivity to both root morphemes and derivations, and how are these mechanisms associated with reading comprehension skill? To answer these questions, we asked children in kindergarten through 6th grade, across a broad spectrum of reading ability, to complete an auditory task of morphological awareness during functional near infrared spectroscopy (fNIRS). We hypothesized that morphological awareness would make a significant contribution to behavioral measures of reading comprehension, and that the brain basis of morphological processing would vary as a function of reading comprehension skill.

Method

Participants

Participants included 97 monolingual English-speaking children (M = 8.62, SD = 1.60, range: 5.92-11.97; 48 boys, 49 girls), across a wide range of reading ability. The sample was 78% White, 19% multiracial or multi-ethnic, and 3% Black or African American. Participating families were of relatively high socio-economic status, with mean parental educational attainment of 8.94 on an 11-point scale, corresponding to some post-baccalaureate or Masters' level schooling. Primary guardians ranged from having some associate's level or certificate training (5) to having a doctorate degree (11).

All participants were typically developing, with normal hearing and vision, and were proficient English speakers, as indicated by English vocabulary standard scores of 85 or above. While we do not use a categorical approach for our main analyses, the present study over-sampled children with dyslexia and reading impairment. Participants were considered reading impaired if they scored at least one standard deviation below the mean on at least two out of four standardized reading assessments, and/or if their parent reported that they had a reading impairment. Fourteen children satisfied both criteria, and eight children were classified as reading impaired based on their task performance alone. Two were identified as reading impaired by their parent, although their performance fell within the typical range on the day of testing. According to these criteria, nearly a quarter of the sample (N = 24, 14 boys, 10 girls, M_{age} = 9.61, SD = 1.81) was considered reading impaired. Notably, none of our reading impaired participants had disproportionately low comprehension skill, but demonstrated consistently poor word reading and phonological awareness, suggesting a possible diagnosis of dyslexia rather than a specific reading comprehension deficit (Landi & Ryherd, 2017).

Behavioral Measures of Language and Literacy

Children completed a one-hour battery of standardized language and literacy assessments. Measures of *reading ability* included the Letter-Word Identification, Passage Comprehension, Word Attack, and Sentence Reading Fluency subtests of Woodcock-Johnson IV (Schrank et al., 2014a). Participants were considered reading impaired if their standard score fell at or below 85 on at least two of these measures.

Receptive vocabulary was assessed using the Peabody Picture Vocabulary Test Fifth Edition (Dunn, 2018). Children heard a word, and were asked to match the meaning of the word to one of four corresponding pictures.

Phonological awareness was assessed using the Comprehensive Test of Phonological Processing (CTOPP-2) Elision subtest (Wagner et al., 2013). Children are asked to repeat a word while removing a phonetic unit. This assessment begins by asking participants to remove a whole syllable (e.g., "Say *cowgirl* without saying *girl*") and progresses to individual phonemes (e.g., "Say ti*m*e without saying /*m*/").

Morphological awareness was assessed using the Early Lexical Morphology Measure (ELMM), which was modeled after the Extract the Base task (Goodwin et al., 2012), and modified to be accessible to a broader range of children. Children heard a word and were asked to complete a sentence using part of that word (e.g., *Noisy. Did you hear that ___?* [noise]). Notably, ELMM is designed to span the elementary school years, and includes both derivational and compound morphology (Marks et al., under review).

Working memory was assessed using the Backward Digit Span task from the Wechsler Intelligence Scale for Children–Fifth Edition (WISC-V; Weschler, 2014). Children heard a series of numbers and were asked to repeat the series in reverse order. The first items included two numbers, and subsequent items included an increasing number of digits.

Brain Basis of Morphological Processing

In the morphological awareness (MA) neuroimaging task, children heard three English words, and were asked to indicate which two words shared a meaningful component. Two of the words presented shared a morpheme (*classroom* and *bedroom*), while one was a phonological distractor that shared the same sounds, but not the same meaning (*mushroom*). During the presentation of the first word (e.g., *bedroom*), children saw a colored rectangle appear at the top of a computer screen. Children then heard two more words in sequence, corresponding to the presentation of a rectangle in the bottom left corner (e.g., *classroom*), followed by a rectangle in the bottom right corner (e.g., *mushroom*) and a question mark. Participants were asked to indicate via button press whether the second word (*classroom*) or the third word (*mushroom*) was a better match for the first word. Children were trained on this "word matching game" immediately prior to neuroimaging. All words used in the task training were distinct from those used in the experimental task.

The MA task consisted of three conditions. In the Root Morpheme experimental condition, children matched words with a shared root (e.g., *spaceship* – *battleship* – *friendship*; or *winner* – *winning* – *window*). In the Affixes experimental condition, children matched words with a shared an inflectional or derivational affix (e.g., *dancer* – *waiter* – *corner*; or *mistake* – *misspell* – *mister*). In the Control condition, children matched whole words (e.g., *lady* – *lady* – *finish*). The Control task was designed to tap into whole word processing, but not awareness of composite morphemes. There were 16 items in each condition, divided into four 30-second blocks of four items each, and separated by a fixed rest period (6 s). The final task had 48 items, and was approximately 7.2 minutes long. The order of the blocks, as well as the order of correct responses was randomized.

Functional NIRS Data Acquisition

We first established a priori brain regions of interest in the perisylvian language and literacy network by using published literature to identify dorsal and ventral inferior frontal, superior temporal and middle temporal regions. We then used the international 10-10 system to build a cap corresponding to these a priori regions, by mounting sources and detectors to a custom-built silicone headband with attached grommets. The final fNIRS probeset included 12 emitters of near-infrared light sources and 24 detectors spaced ~2.7 cm apart in a grid-like shape. This yielded 46 source-detector pairings or data channels, with 23 channels per hemisphere that covered frontal, temporal, and temporo-parietal regions (see Appendix C, Figure C.1). We digitized the geometric structure of the cap on a mannequin foam head using a Polhemus Patriot 6 Degree-of-Freedom Digitizer. The coordinates provided by the digitizer were processed in AtlasViewer GUI, a MATLAB-based software (Aasted et al., 2015), and transformed to Montreal Neurological Institute (MNI) stereotactic space. Estimated regions covered by each channel and midpoint MNI coordinates are detailed in Appendix C.

fNIRS data were collected using a TechEN-CW6 system with 690 and 830 nm wavelengths at a sampling frequency of 50 Hz. Techen-CW6 software signal-to-noise ratio (SNR) minimum and maximum were set to the standard 80 dB and 120 dB range, respectively. For each participant, probes were applied using the international 10-10 transcranial system positioning (Jurcak et al., 2007). Trained experimenters identified the nasion, inon, Fpz, and left and right pre-auricular points, head circumference were measured and F7, F8, T3, and T4 were anchored to a specific source or detector. Cardiac signal at each channel was monitored to ensure the quality of optode placement.

Data Processing and Analysis

The subject- and group-level analyses were completed with the NIRS Brain AnalyzIR Toolbox (Santosa et al., 2018), a MATLAB (Mathworks, MA) based software. At the subject level, we trimmed each raw data file to keep only 5 seconds of pre- and post- experimental task baseline data, and resampled the data from 50Hz to 2Hz given that the fNIRS signal of interest lies in the range of 0-1 Hz. We converted optical density data to hemoglobin concentration change data using the modified Beer-Lambert Law. Each participant's hemoglobin concentration data was then analyzed using a general linear model (GLM) with prewhitening and robust least square regression (Barker et al., 2013; Friston et al., 2007). We used an autoregressive filter combined with a weighted least square (WLS) estimation approach to eliminate the non-spherical noise structure caused by physiological and motion artifacts in the time series (Barker et al., 2013; Caballero-Gaudes & Reynolds, 2017; Friman et al., 2004). The pre-whitening autoregressive filter cleans the temporal serial correlation in the data while the weighted least square estimation adjusts the contribution weight of noisy time points during the model coefficient estimation process. We modeled the canonical hemodynamic response function to peak 6-seconds after trial onset (Friston et al., 2007). The temporal and dispersion derivatives were added to the canonical HRF function as well as the DCT matrix to account for signal drift over time. The single subject GLM yielded estimated individual-level regression coefficients for HbO (oxygenated hemoglobin) and HbR (deoxygenated hemoglobin) signal, each condition, and each channel.

Group-level analyses were then conducted using linear mixed-effects models for each data channel. In the group-level GLM, we modeled task condition (control, roots, and affixes) as a fixed effect, participant as a random effect, and the individual-level beta values for HbO and HbR as the predicting dependent variables, including age and socioeconomic status as covariates. In the second group-level GLM, we included the interaction between task condition and reading comprehension ability, and modeled vocabulary knowledge as a covariate. Estimated group-level channel-based effects were extracted for the contrasts experimental condition(s) > control. We then plotted the group-level effects (unstandardized betas) for each contrast on the MNI 152 brain template using the previously digitized MNI coordinates. The analyses presented below focus on HbO as it accounts for a larger portion of the signal (HBO 76%; HBR 19%), in part because fNIRS instruments such as TechEN CW6 capture the HBO signal with greater reliability (Gagnon et al., 2012), and only include effects that survived FDR correction for multiple comparisons.

Results

Language and Reading Skill

Descriptive statistics for all language and literacy measures are presented in Table IV.1. Participants had high-average language ability, with a mean vocabulary standard score of 115.76. Mean standard scores on standardized literacy assessments fell within the typical range, between 98 and 106. However, *N* = 24 participants were considered reading impaired (*N* = 22 of whom scored 85 or below on two or more literacy tasks, and two who were identified as reading impaired by their parents). At the other end of the spectrum, *N* = 25 were highly precocious readers, scoring 115 or above on two or more literacy tasks. Participants thus spanned a wide range of reading proficiency.

Table IV.1 *Study 3 descriptive statistics*

	M	*(SD)*	Range
Age	8.62	(1.60)	5.92–11.97
Parental education	8.94	(1.71)	5–11
Vocabulary[1]	115.76	(16.20)	85–160
Word reading[1]	104.21	(18.77)	46–136
Decoding[1]	106.24	(15.59)	59–136
Passage comprehension[1]	98.85	(17.06)	40–127

Sentence reading fluency[1]	102.47	(18.01)	42–138
Phonological awareness[2]	9.93	(2.66)	3–15
Morphological awareness[3]	28.85	(8.56)	2–40
Working memory[3]	7.53	(1.96)	3–13

Note. *N* = 97. [1]Standard score, typical range: 85-115

Children successfully completed the fNIRS Morphological Awareness task with high accuracy. The Affixes condition of the neuroimaging task was most challenging, with a mean accuracy of 63.88% (*SD* = 15.23%), followed by the Roots condition, with a mean accuracy of 84.47% (*SD* = 11.34). Accuracies were significantly higher ($t(95) = 16.96$, $p < .001$), and response times were significantly faster ($t(95) = -5.33$, $p < .001$) on Roots than Affixes. Children performed near ceiling on the control condition, with a mean accuracy of 94.55% (*SD* = 8.21%). Correlations between language and literacy variables, as well as overall fNIRS task accuracy, are presented in Table IV.2. Note that the highest correlations were found between fNIRS task accuracy and word reading ($r = 0.50$, $p < .001$) as well as reading comprehension ($r = 0.44$, $p < .001$).

Table IV.2 *Partial correlations between language and literacy variables*

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1. Vocabulary	-							
2. Word reading	0.44***	-						
3. Decoding	0.40***	0.86***	-					
4. Passage comp	0.51***	0.85***	0.73***	-				
5. Reading fluency	0.44***	0.73***	0.60***	0.73***	-			
6. Phon. awareness	0.40***	0.65***	0.70***	0.64***	0.51***	-		
7. Morph. awareness	0.35**	0.66***	0.57***	0.65***	0.47***	0.47***	-	
8. Digit span	0.08	0.25*	0.16	0.24*	0.16	0.19	0.17	-
9. fNIRS task accuracy	0.20	0.50***	0.35**	0.44***	0.31**	0.27*	0.34**	0.12

Note. Raw scores, controlling for age.

Morphological Awareness and Reading Comprehension

We used hierarchical regression to test our hypothesis that morphological awareness is related to reading comprehension (Table IV.3). At step 1, we entered children's age, parental educational attainment, and whether or not they were classified as reading impaired. At step 2, guided by the Simple View of Reading, we entered vocabulary knowledge (PPVT; Dunn, 2018) and decoding skill (Word Attack; Schrank et al., 2014a). Finally, at step 3, we entered two measures of morphological awareness: ELMM score, and accuracy on the MA neuroimaging task. The final model accounted for 83% variance in reading comprehension. Results showed that age (β = 0.21, t = 2.32, p = .023), reading impairment (β = -0.29, t = 4.14, p < .001), decoding ability (β = 0.26, t = 3.60, p = .001), and morphological awareness as measured by ELMM (β = 0.29, t = 3.54, p = .001), and accuracy on the fNIRS task (β = 0.13, t = 2.33, p = .022) were all significant predictors of reading comprehension skill. Once morphological awareness was added to the model, vocabulary was no longer a significant predictor of reading comprehension (β = 0.12, t = 1.56, p = .123).

Table IV.3 *Hierarchical regression explaining variance in reading comprehension*

	Std β	t	p	R	R^2	ΔR^2
Step 1				0.825	0.681	
Intercept		-0.63	.533			
Age	0.78	11.89	<.001			
Parental education	-0.01	-0.10	.924			
Reading impaired?	-0.64	-9.02	<.001			
Step 2				0.880	0.755	0.094
Intercept		-1.68	.098			
Age	0.36	3.73	<.001			
Parental education	-0.02	-0.39	.696			
Reading impaired?	-0.36	-4.67	<.001			
Vocabulary	0.19	2.19	.032			
Decoding	0.39	4.96	<.001			

Step 3				0.911	0.830	0.056
Intercept		-2.56	.012			
Age	0.21	2.32	.023			
Parental education	-0.01	-0.23	.817			
Reading impaired?	-0.29	-4.14	<.001			
Vocabulary	0.12	1.56	.123			
Decoding	0.26	3.60	.001			
Morphological awareness	0.29	3.54	.001			
fNIRS task accuracy	0.13	2.33	.022			

Note. N = 87 with complete data. Final $F(7, 80) = 55.94$, $p < .001$.

To test whether morphological awareness made a similar contribution to reading comprehension across a broad range of reading skill, we conducted a second post-hoc regression that included two additional reading impairment × morphological awareness interaction terms, one for each measure of morphology. Neither interaction was significant, indicating that both typical and impaired readers were relying on morphological awareness to a similar extent.

Brain Basis of Morphological Processing

Our first step in analyzing the neuroimaging data was to examine the brain basis of morphological processing across all participants. Compared to the resting baseline, our MA task incurred widespread activation in perisylvian language regions, including bilateral inferior frontal gyrus, primary auditory cortex, superior/middle temporal gyrus, and supramarginal gyrus (Figure IV.1).

We then examined brain activity specific to the Root Morpheme condition (*winner* – *winning* – *window*) and the Derivational Affixes condition (*dancer* – *waiter* – *corner*). The within-group comparison for the Affixes > Control contrast revealed that, compared to whole word processing, attention to derivations involved significantly greater activation in left middle/inferior frontal gyrus (MFG/IFG) and posterior temporal regions. The Roots > Control contrast revealed that, compared to whole word processing, attention to root morphemes also incurred significantly greater activation in left MFG and IFG, as well as the left superior temporal gyrus (STG), and middle/inferior temporal gyrus (MTG/ITG). A comparison of Affixes > Roots revealed greater inferior frontal and precentral activation for affixes, and greater temporal lobe activation for roots. Affixes also incurred less substantial occipitotemporal deactivation than Root Morpheme processing. Beta values for comparisons between conditions are detailed in Table IV.4.

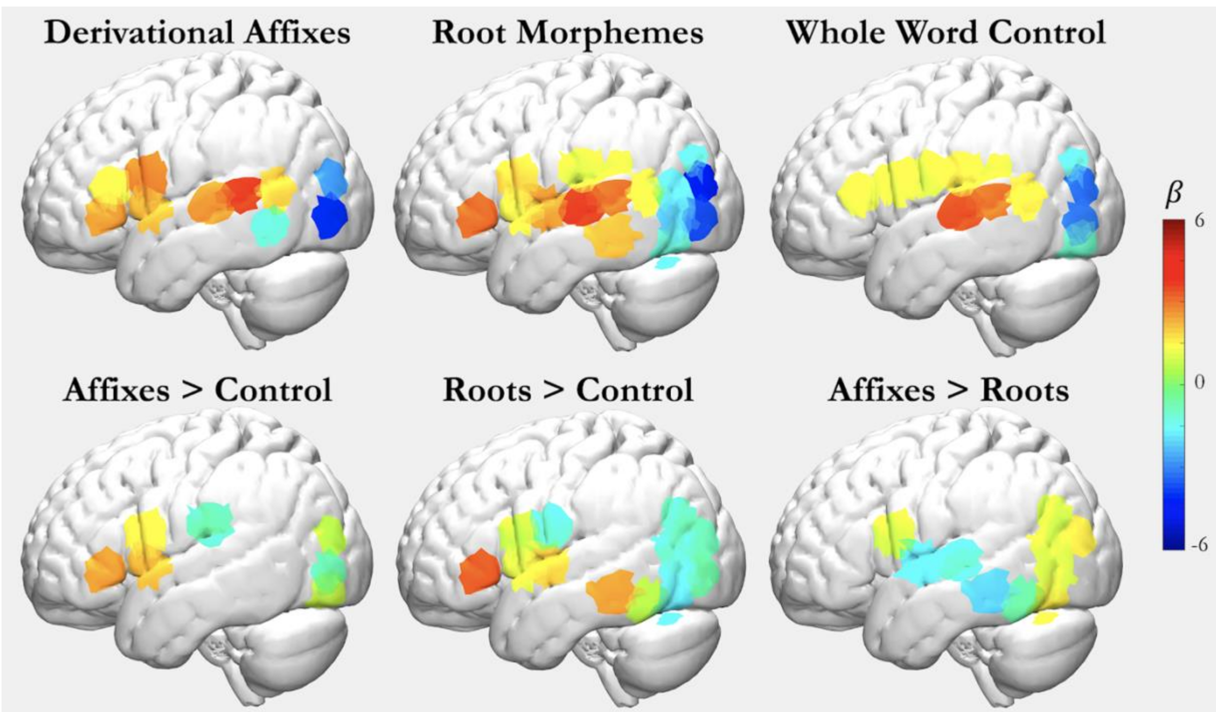


Figure IV.1 *Brain activity during the morphological awareness task conditions*

Interaction with Reading Comprehension Skill

Our next aim was to examine the association between reading comprehension skill and the brain basis of morphological processing. To do this, we ran another GLM in which we modeled the main effects and interaction between task condition (derivational affixes, root morphemes and control) and children's reading comprehension standard score, including vocabulary standard score as a covariate. Results demonstrated a significant interaction between reading comprehension and morphological processing in largely left-lateralized language regions of the brain. Common to both the Roots and Affixes condition, children with better reading comprehension demonstrated increased activation in the left ventral IFG/anterior STG, and right posterior STG. Better reading comprehension was also associated with lower engagement of right posterior temporal/occipital cortex. During the Derivations condition specifically, we observed additional brain-behavior associations in the left vIFG, MTG and IPL, as pictured in Figure IV.2 (see also Table IV.5). Children with better reading comprehension demonstrated a greater increase in activation for Derivations in the IFG and MTG, and less deactivation in the IPL.

Table IV.4 *Brain-behavior interactions with reading comprehension*

H	Channel	Region	β	*T*-stat	*p*	*q*
Root Morphemes > Whole Word Processing						
L	1.1	vIFG, MFG	3.25	8.93	<.001	<.001
L	1.3	vIFG, Precentral	1.32	3.37	.001	.003
L	1.4	dIFG, MFG	0.74	3.01	.003	.008
L	2.3	Precentral, STG, IFG	2.08	3.99	<.001	<.001
L	5.5	MTG, STG	2.49	8.05	<.001	<.001
L	5.11	ITG, MTG, FG	0.71	3.24	.001	.004
R	6.12	ITG, IOG, MOG, FG	0.88	3.25	.001	.004
Derivational Affixes > Whole Word Processing						
L	1.1	vIFG, MFG	2.58	6.14	<.001	<.001
L	1.3	vIFG, Precentral	2.24	4.91	<.001	<.001
L	1.4	dIFG, MFG	1.63	5.67	<.001	<.001
R	2.4	IFG, Precentral, MFG	1.15	2.83	.005	.016
L	4.9	MTG, AG, STG, SMG	0.70	2.69	.007	.022
L	6.12	ITG, IOG, MOG, FG	0.84	2.60	.010	.027
Roots > Affixes						
R	1.1	vIFG, MFG	1.06	-3.21	.001	.007
L	2.3	Precentral, STG, IFG	1.74	-2.66	.008	.032
L	2.5	Postcentral, STG, Precentral	1.00	-2.50	.013	.047
L	5.5	MTG, STG	2.21	-5.54	<.001	<.001
R	6.9	MOG ITG, FG, MTG	2.16	-4.58	<.001	<.001
R	6.11	MOG, MTG, ITG	2.25	-5.29	<.001	<.001
R	6.12	ITG, IOG, MOG, FG	4.42	-15.68	<.001	<.001

Affixes > Roots						
L	1.4	dIFG, MFG	0.89	2.84	.005	.021
R	2.5	Postcentral, STG, Precentral	1.06	2.76	.006	.026
L	4.7	SMG, STG, MTG, IPL	1.03	3.90	<.001	.001
L	4.8	IPL, SMG, AG	0.86	2.47	.014	.048
L	4.9	MTG, AG, STG, SMG	1.53	5.44	<.001	<.001
L	6.7	MTG, STG, MOG, ITG	1.10	3.21	.001	.007
L	6.11	MOG, MTG, ITG	1.59	4.42	<.001	<.001

Note. L = left hemisphere; R = right hemisphere. Channel = Source.Detector. *q* = significance level after FDR correction. d: Dorsal; v: Ventral; IFG: Inferior Frontal Gyrus; MFG: Middle Frontal Gyrus; STG: Superior Temporal Gyrus; IPL: Inferior Parietal Lobule; MTG: Middle Temporal Gyrus; TTG: Transverse Temporal Gyrus; SMG: Supramarginal Gyrus; AG: Angular Gyrus; ITG: Inferior Temporal Gyrus; FG: Fusiform Gyrus; MOG: Middle Occipital Gyrus; IOG: Inferior Occipital Gyrus. Regions are reported in the order of greatest probability for each channel.

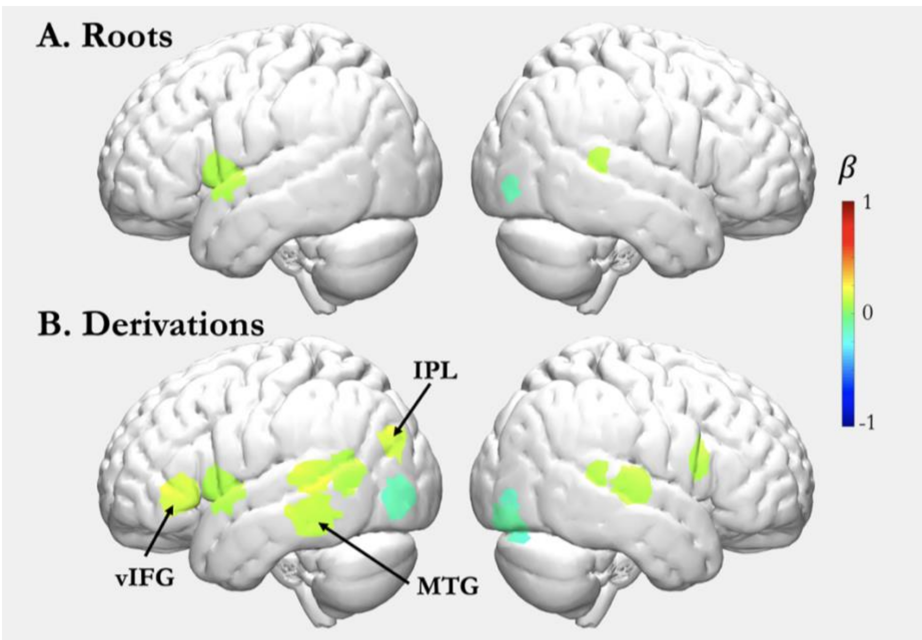


Figure IV.2 *Interaction between reading comprehension skill and morphological awareness task activity*

Discussion

This study asked two main questions. First, how does morphological awareness support reading comprehension in children with and without reading impairment? Second, how is the brain basis of morphological processing associated with skilled reading comprehension? To answer these questions, we analyzed behavioral and fNIRS neuroimaging data from a large sample of children across a wide range of reading ability. At a behavioral level, we found that morphological awareness made a substantial contribution to reading comprehension in typical and impaired readers. At a neural level, we discovered an interaction between reading comprehension skill and brain activation during morphological processing in left inferior frontal, middle temporal, and inferior parietal brain regions often associated with reading development. These results shed new light on the role of morphological awareness in reading comprehension and the neural mechanisms supporting this association in children across a broad range of reading abilities.

Morphological Awareness Contributes to Reading Comprehension

There has been some disagreement in the field as to the role of morphological awareness in reading for children with dyslexia. Many studies have reported lower performance on tasks of morphological awareness compared to age-matched controls (Berthiaume & Daigle, 2014; Casalis et al., 2004; Kearns et al., 2016; Tsesmeli & Seymour, 2006). At the same time, others suggest that morphological awareness might be a relative strength or a compensatory factor for impaired readers (Deacon et al., 2019; Law et al., 2018). This study examined the contribution of morphological awareness to reading comprehension in both typical and impaired readers. We examined the possibility of an interaction between a binary classifier of reading impairment and morphological awareness and found no evidence for an interaction, suggesting that both typical and impaired readers were relying on morphological awareness to a similar extent.

More specifically, our findings suggest a relation between reading comprehension and morphological awareness, measured both within the sentence context and at the single word level. Our sentential measure asked children to complete a sentence by extracting the base of a complex word, as in "*Colorful.* That flower is such a pretty ___ [color]." Our neuroimaging task presented children with three individual words (e.g., *farmer* - *waiter* - *corner*) and asked children to identify the two that shared a morpheme (*farm+ER* and *wait+ER*). Both measures assessed children's sensitivity to compound and derivational morphology. We found that each morphology measure made a unique contribution to participants' reading comprehension, and together accounted for an additional 5.6% of variance explained, above and beyond the contributions of demographic factors, vocabulary knowledge and decoding skill.

This new evidence contributes to the growing body of work advocating for the importance of morphological awareness in the reading process across a wide range of ages, skill levels, and languages (e.g., Arabic: Vaknin-Nusbaum & Saiegh-Haddad, 2020; Chinese: Cheng et al., 2017; Pan et al., 2016; French and Greek: Desrochers et al., 2018). In English, numerous studies have revealed both direct and indirect relations between morphological awareness and reading comprehension (Deacon et al., 2014; Kieffer & Lesaux, 2012; Levesque et al., 2017). Our present findings extend this evidence, demonstrating a robust contribution of morphological awareness to reading comprehension in readers across a wide range of literacy skill.

Brain Basis of Morphological Processing

Current models of the neurobiology of dyslexia have been largely informed through phonological reading tasks, such as rhyme judgement tasks (Hoeft et al., 2007; Kovelman et al., 2012; Tanaka et al., 2011). While phonological processes are often seen as a stepping stone to learning to read, the ability to recognize larger units of meaning is essential for later literacy and successful reading comprehension (Rastle, 2018). Yet, little is known about the brain basis of morphological awareness, or the extent to which it might vary in impaired readers.

The present study used fNIRS to investigate the neurocognitive mechanisms associated with morphological processing in the auditory modality. Children heard three words and identified the two words that shared a meaningful component. Our experimental design contrasted three conditions: a root morpheme matching condition (*teacup* - *teapot* - *T-rex*), an affix matching condition (*reset* - *replay* - *reading*), and a whole word processing control. We focus on the auditory modality for two reasons: first, because the brain basis of spoken word processing precedes and predicts successful reading development (Marks et al., 2019), and second, to ensure that performance was not confounded by single word reading ability in participants with dyslexia.

Careful examination of the neural processes associated with each condition revealed both common and task-specific patterns of brain activity. Whole word, root morpheme, and derivational affix processing all recruited bilateral auditory language processing regions (IFG and STG), and demonstrated relative deactivation of posterior brain regions. Compared to the whole word processing control, the two morphological awareness conditions both revealed greater engagement in several hubs of the semantic system (Binder et al., 2009). Processing root morphemes incurred greater left temporal activity than whole words, especially in left MTG, a region associated with lexical or semantic retrieval (Binder et al., 2009). Roots also incurred greater activation in the left IFG and anterior STG. The IFG has been associated with phonological, semantic, and syntactic processing (Vigneau et al., 2006). More specifically, the ventral aspect of the IFG (BA 47) is typically associated with complex semantic retrieval analyses, and the more dorsal aspect of the active left IFG (BA 45/44) region is typically associated with both phonological (Ip et al., 2019) and morpho-syntactic (Skeide & Friederici, 2016, Kovelman et al., 2008) language processes. Activity in the anterior STG is associated with syntactic complexity (Brennan et al., 2012). Notably, Arredondo and colleagues (2015) similarly reported IFG and aSTG activation during a morphological judgment task with children.

Similar to the Roots condition, Affixes also incurred greater left frontal and temporal activity than whole word processing. In particular, wider-spread prefrontal activity suggests this condition was more effortful, as also demonstrated by children's lower accuracy and higher response times. This is logical as affixes cannot stand alone, and are thus more semantically abstract and potentially more analytically demanding. Together, these results speak to the multifaceted nature of morphological processing, which requires one to connect analysis of a word's underlying structure to representations of meaning.

Brain-Behavior Associations with Reading Comprehension Skill

To uncover the relation between reading comprehension and the neural bases for morphological awareness, we examined the interaction between participants' reading comprehension and their brain activity during the morphological awareness task. We observed an interaction between reading ability and engagement of the left IFG/anterior STG and right posterior STG regions common to both the Roots and Derivations condition. Furthermore, children with better reading comprehension showed greater engagement of the left ventral IFG, left MTG, and left IPL associated with Derivations specifically. Notably, hypoactivation in left IFG, MTG and IPL have all frequently been reported in studies of dyslexia (Richlan, 2014; Shuai et al., 2019).

The locations of these brain-behavior interactions are closely aligned with theoretical models of auditory word processing and literacy development. In particular, beginning word reading largely relies on frontal (IFG) and dorsal (STG/IPL) circuits associated with phonological analysis and integrating phonological and orthographic information (Pugh et al., 2000; Shuai et al., 2019). Furthermore, the left ventral IFG/anterior STG region is thought to be involved in building syntactic structure during language processing (Bemis & Pylkkänen, 2013; Brennan et al., 2012). In the MA task, both the Roots and Affixes conditions require structural analyses for the morpho-phonological segmentation of spoken words, and specific attention to mapping units of sound onto units of meaning. Our findings suggest that perhaps better readers can more effectively tap into the phonological and structural analyses associated with these brain regions, a processing feature that cascades to benefit their text reading abilities.

Of particular note are the Derivational Affix-specific associations with reading comprehension in the parietal lobe. Numerous studies have pointed towards functional and structural differences in the inferior parietal region in dyslexia across a variety of tasks, leading to several possible explanations for this association between reading comprehension and IPL activity. One possibility is that reduced IPL activity may be associated with phonological deficits. Studies of impaired readers frequently report relatively lower engagement - or greater task-related deactivation - of left IPL during phonological awareness tasks. For instance, Hoeft and colleagues (2007) reported greater deactivation among children with dyslexia during a visual word rhyme judgment, as well as reduced grey matter volume compared to both age-matched and reading-level-matched controls. Alternatively, this brain-behavior association could be associated with a specific semantic deficit. Reduced IPL activity has been observed during semantic judgements, both at the single-word level (Booth et al., 2007), and in sentence processing (Schulz et al., 2008). Landi and colleagues (2010) discovered that adolescents with dyslexia under-activate left inferior parietal regions during both phonological and semantic processing, in both the auditory and visual modalities. In line with this prior work, our findings similarly suggest that impaired readers with poor comprehension skill show greater deactivation in left inferior parietal regions during a morphological awareness task. This effect was more robust during the Derivations condition than the Roots condition, likely due to the semantically abstract and analytically complex nature of derivational morphology. As the IPL is classically associated with integrating phonological, semantic, and orthographic representations, these results suggest that poor readers may struggle to efficiently manipulate and integrate units of sound and meaning.

Theoretical Implications

Our neuro-cognitive findings support and extend theories of reading comprehension. The Reading Systems Framework (Perfetti & Stafura, 2014) suggests that morphology should contribute to reading comprehension at both the single word level as well as the sentence level. We complement this perspective by demonstrating that morphological awareness makes a significant contribution to passage comprehension, likely through its role at both single-word and sentence-processing levels, in both typical readers and those with dyslexia. Going one step further, Kirby and Bowers' (2017) Binding Agent Theory prompts us to consider morphology as the "glue" that connects and integrates mental representations of phonology and semantics to one another, and to orthography. The robust engagement of the neural networks often associated with syntactic, semantic, and phonological, and orthographic language processes further reinforces this perspective. Binding may take place at the level of language processes, as suggested by activations in language-associated regions, and/or in the IPL region classically associated with speech-to-print mapping. These findings suggest that successful reading comprehension, and its deficit in impaired readers, may relate to children's ability to efficiently integrate the units of sound and meaning in speech. The present study thus helps to bridge our understanding of children's sensitivity to morpho-phonological language structure to theories of reading comprehension.

Future Directions

The present study examined the neurocognitive basis of morphological processing in typically developing and impaired readers, ages 5-11. To the best of knowledge, the present work is the first to suggest that children's activation in left parietal regions' functionality modulates the relation between morphological awareness and reading comprehension. One particular strength of the current study is its methodological approach, which combines neural and behavioral measures in a relatively large sample of readers across a wide range of reading proficiency. As reading (dis)ability falls along a broad spectrum, with many possible areas of weakness for struggling readers, we did not dichotomize our sample to compare the association between morphology and reading comprehension across groups. Nevertheless, future research may be interested in a direct comparison between clinically impaired and typically developing readers.

Notably, our behavioral measures are not as extensive as might be possible in a behavioral-only approach. the present measures were limited to only two tasks of morphological awareness while there are many others that tap into morphological analyses in greater detail (Goodwin et al., 2017; Levesque et al., 2019). The relation between these two morphological skills, and the neurocognitive processes that support them both, are important directions for future research. Furthermore, we recognize that our sample was of relatively high SES, which may impede the generalizability of our findings.

Conclusions

The present study sheds light on the association between morphological awareness and reading comprehension, and the neurocognitive mechanisms underlying this association, in typical and impaired readers. Our findings add to a growing body of knowledge indicating the importance of morphology for successful reading. We provide some of the first evidence of the distinct neurocognitive processes underlying root and derivational morphological processing in developing readers, and reveal an interaction between morphological processing and reading skill. Our findings indicate that better reading comprehension is associated with increased activation in left hemisphere brain regions associated with language processing and speech-to-print mapping. These findings not only underscore the importance of morphological awareness for successful reading development, but highlights the specific importance of derivational morphology for reading comprehension in English.

CHAPTER V. General Discussion

This dissertation addresses two longstanding questions in Educational Psychology and Educational Neuroscience. First, what elements of spoken language proficiency best support children's early literacy development and neural organization for learning to read? Second, does variation in children's early language experiences and learning (dis)ability influence literacy development and its emerging neural architecture?

It has been long understood that language and literacy are interrelated, and that learning to read builds on children's existing language skills. However, the mechanisms by which reading builds on language, both behaviorally and in the brain, are less clear. Through three interrelated studies, this dissertation examined the mechanisms underlying this association between spoken and written language.

Situating Findings Within a Larger Theoretical Model of Reading

The findings of this dissertation advance the Lexical Quality Hypothesis (Perfetti & Hart, 2002; Perfetti, 2007), which suggests that successful literacy depends on closely connected representations of sound, meaning, and print.

First, Study 1 tested the Lexical Quality framework by examining the spatial overlap in the neural mechanisms for spoken language processing (accessing sound and meaning in the auditory modality), and print processing. This study suggested that children's spoken language proficiency statistically predicts the extent of their print-speech neural convergence in kindergarten. Examined longitudinally, this overlap in brain activity for print and speech in kindergarten predicted word reading outcomes one year later, in 1st grade. Interpreted through the Lexical Quality lens, print-speech convergence may be understood as a way to physically quantify the interconnections between the components of word knowledge, which in turn support fluent word recognition.

These findings (Figure V.1) have three key implications. First, the discovery that spoken language competence is the antecedent of neural convergence aligns with behavioral research suggesting the foundational role of language in learning to read. Second, the finding challenges prior neuroimaging work suggesting that such neural convergence is the result of proficient reading (Rueckl et al., 2015). Finally, the longitudinal findings address the long standing dilemma on how to best conceptualize early literacy, and the transition from speech to print, by highlighting the reciprocal nature of language and literacy development.

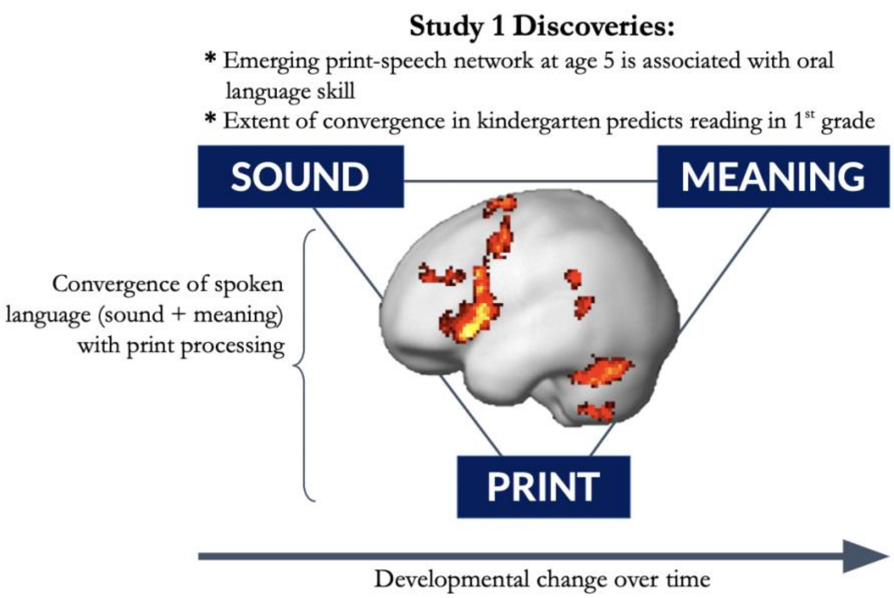


Figure V.1 *Study 1 discoveries*

Studies 2 and 3 narrowed the scope of inquiry from “spoken language,” broadly defined, to precise sub-lexical skills. More specifically, in Studies 2 and 3, I investigated more granular components of spoken word processing, drilling down from the whole word level to children’s sensitivity to individual units of meaning (*morphemes*). These studies focused on children’s *morphological awareness,* or their tacit knowledge of, and sensitivity to, morphemes in language. Morphological awareness may be understood along developmental continuum from implicit awareness to an explicit understanding of morphology over the course of schooling (Carlisle, 2004). Dissertation Studies 2 and 3 examine children’s implicit morphological knowledge, and its relation to both word reading and reading comprehension.

Study 2 tested Lexical Quality Hypothesis (Perfetti, 2007), and its extension in Binding Agent Theory (Kirby & Bowers, 2017), by investigating morphological skills as a binding element between children’s emerging spoken and orthographic word competence. Study 2A suggested that morphological awareness is associated with literacy, even among beginning readers in the first years of schooling. Study 2B further indicated that the association between morphological awareness and reading outcomes is influenced by children’s bilingual language experience. Consistent with a usage-based theory of language acquisition, children’s reading skill appeared to benefit from their proficiency with morphemic features that were not reinforced by their home language (discussed further below).

The findings of Study 2 (Figure V.2) have important implications for both theory and practice. First, the discovery that morphological awareness is a significant statistical predictor of word reading in kindergarten and 1st grade readers advances the novel Binding Agent Theory (Kirby & Bowers, 2017). Morphology is not a common component of early literacy curricula, yet these findings provide support for the idea that early instruction may benefit later reading outcomes (e.g., Goodwin & Ahn, 2013). Furthermore, these results advance our understanding of the individual variability in literacy acquisition, and drive home the importance of considering children's linguistic experiences at home when planning optimal instruction.

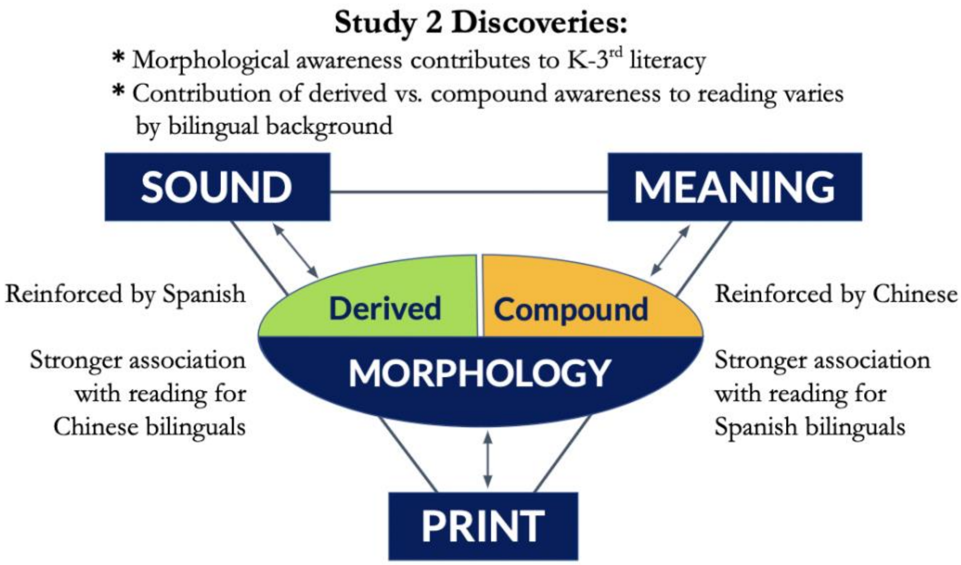


Figure V.2 *Study 2 discoveries*

Finally, Study 3 tested the Binding Agent framework (Kirby & Bowers, 2017) through a neuro-cognitive lens, by examining the brain bases of morphological processing and their relation to reading ability. First, Study 3 revealed distinct patterns of brain activity associated with processing derived and compound spoken words. As little is known about the brain basis of English morphology, particularly in children (Leminen et al., 2018), this study makes a critical contribution to understanding the neural underpinnings of both derivational and compound morphological processing. The findings of Study 3 further revealed that the neural correlates of morphological processing may vary as a function of reading (dis)ability.

These results (Figure V.3) further our theoretical understanding of reading comprehension and its impairment in dyslexia. Findings also advance the Binding Agent Theory

(Kirby & Bowers, 2017), by demonstrating that morphological processing in skilled readers engages left parietal regions involved in integrating sound, meaning, and print. Finally, as the majority of research into the neurocognitive underpinnings of dyslexia has been based on phonological processing tasks, findings shed important new insight into how other sub-lexical processes may vary in children with reading impairment. By identifying brain regions associated with specific sub-lexical components of spoken word processing that are associated with better reading, Study 3 may lend precision to our understanding of the converging print-speech network from Study 1.

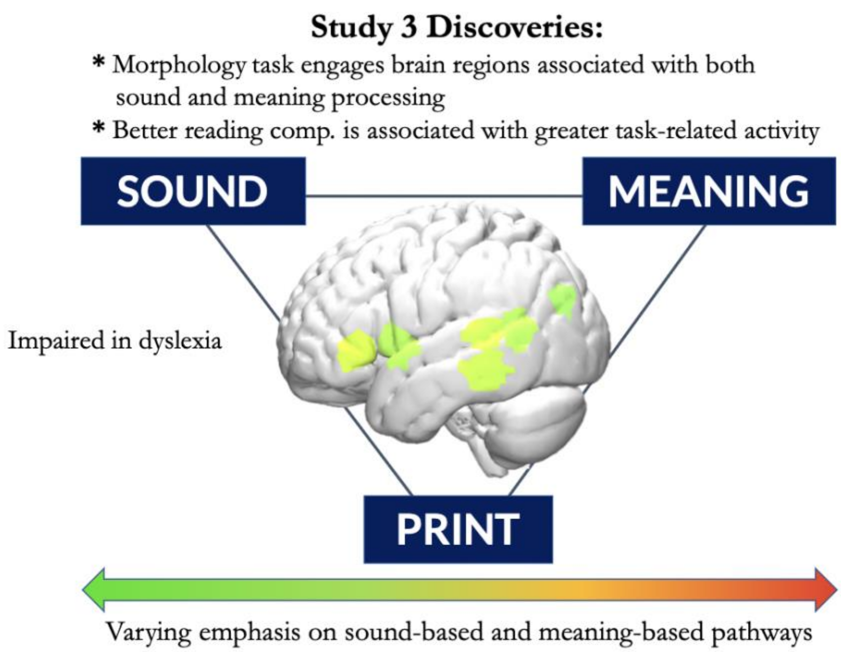


Figure V.3 *Study 3 discoveries*

Theoretical Implications

Centering Morphological Awareness

The field currently lacks a theoretical consensus around the role of morphological awareness in early reading development. Emerging perspectives have suggested that morphology may be a “binding agent” that connects representations of phonology, semantics, and print (Kirby & Bowers, 2017). Yet while some theories suggest that knowledge of both sounds and meanings should contribute to word reading at any stage (Perfetti, 2007; Perfetti & Stafura, 2014), others have suggested that morphological awareness may not contribute to literacy acquisition until children are proficient word readers, in mid-to-late elementary school (Ehri, 2014). This dissertation demonstrates the unique contributions of morphological awareness to reading outcomes in children as young as 5 or 6 years old, above and beyond phonological awareness, vocabulary (semantics), and demographic factors. This replicated finding across Studies 2 and 3 lends credence to idea that morphology may be understood as a unique component of word knowledge that supports fluent literacy, and provides neurocognitive evidence in support of both the Lexical Quality Hypothesis (Perfetti, 2007) and Binding Agent Theory (Kirby & Bowers, 2017).

Beyond the discussion of morphology as a binding agent in general, Studies 2 and 3 additionally consider the role of specific morphological structures. Both chapters reveal robust contributions of derivational and compound morphological awareness to reading, while also demonstrating that the brain processes derivational and free root morphemes differently. Furthermore, Study 3 reveals that the brain bases of morphological processing are associated with children’s literacy skill, demonstrating that poor readers under-engage parietal regions implicated in syntactic, semantic, phonological, and combinatorial language processes during a morphology task. This finding makes a substantial contribution to the literature, as little is known about brain development for morphological awareness, nor its association with literacy acquisition. Not only does Study 3 provide first-time evidence linking reading ability to neurocognitive differences in morphological processing, it also suggests neural mechanisms by which morphological processing may effectively "bind" representations of sound, meaning, and print in the mind and brain. Together, these studies point to the importance of spoken word processing in the brain as the foundation of reading success. They suggest a continuous developmental mechanism by which language development, and the integration of various components of word knowledge, lay the foundation for learning to read.

Diverse Populations of Learners

By systematically varying bilingual language exposure and reading aptitude, this dissertation sheds new light on the interplay between language proficiency, neural architecture for language processing, and literacy outcomes. In Study 2, I used bilingualism as a lens to examine the impact of diverse linguistic experiences on mechanisms for reading. Results revealed contrasting bilingual effects on the association between English morphological awareness and word reading. Among Spanish-English bilinguals, who had extensive experience with derivational morphology in both Spanish and English, sensitivity to compound morphology (e.g., *snow+man*) was predictive of word reading; in contrast, among Chinese-English bilinguals, who had extensive experience with compound morphology in both Chinese and English, sensitivity to derivational morphology (e.g., *snow+y*) was predictive of word reading. In other words, variability in children's English reading skill was associated with their sensitivity to English-specific morphemic features that were not reinforced by their home language. This finding has clear implications for educators, suggesting that proficient or balanced bilingual children may benefit from learning activities that bolster their sensitivity to less familiar English structures.

In Study 3, I examined variability in reading aptitude by oversampling children with dyslexia or reading impairment. Dyslexia is typically associated with deficits in phonological awareness and single word reading. As such, the lion's share of prior work on the neurobiology of reading impairment has centered around phonological processing tasks such as rhyme judgments (Norton, Beach & Gabrieli, 2015). However, Study 3 suggests that reading (dis)ability is also associated with brain differences during morphological processing, with poor readers showing relative hypoactivation for morphology in left frontal and parietal regions. Brain-behavior associations demonstrate that morphological processing – and sensitivity to derivational affixes specifically – varies as a function of reading skill along both dorsal (sound-based) and ventral (meaning-based) routes. This finding extends prior work that has primarily suggested differences in dorsal regions associated with sound processing or print-speech integration that are associated with single word reading. By examining morphological processes, and their association with reading comprehension instead of single word identification, we find new evidence that engagement of the ventral network may also be modulated by reading (dis)ability. At the same time, this dissertation also leaves many open questions about the role of morphology in literacy for impaired readers, and the extent to which morphological awareness may be an extension of, or dissociable from, phonological awareness. Future research should continue to examine morphological processing, and the neural basis of integrating sound, meaning, and print, to further inform our understanding of reading impairment.

Practical Implications

This dissertation demonstrates that greater morphological awareness is associated with better reading performance. This suggests that increased morphological instruction in elementary classrooms may benefit young readers. Indeed, short morphological interventions (e.g., 30 minutes of morphological training a week for three months; Lyster et al., 2016) have been linked with improved long-term reading outcomes, and a meta-analysis of morphological instruction in the classroom suggests largest effect sizes for young learners (Goodwin & Ahn, 2013). We must therefore consider how morphological awareness could be incorporated more broadly and emphasized in existing curricula, as well as both the instructional strategies and child-level factors that may best support successful reading development.

One major goal in the field of Educational Psychology is to use the science of reading to improve instruction. Educators have long debated the efficacy of centering reading instruction around *code* or *meaning* (Connor, Morrison, & Katch, 2004). Code-focused instruction typically focuses on developing students' phonological awareness and sound-to-print mapping skills, often resulting in curricula centered around phonics. Meaning-focused instruction, in contrast, generally aims to train students' rapid word recognition and comprehension skills. This often translates into a "whole language" approach, in which teachers spend minimal time on phonics and decoding, and instead work to immerse their children in a rich language environment to enhance their vocabulary knowledge and love of reading.

Considered through the lens of the Binding Agent Theory (Kirby & Bowers, 2017), morphological instruction may be considered both code-focused and meaning-focused. First, morphology connects phonology and orthography, providing information about word segmentation, pronunciation and decoding. Within the context of code-focused instruction, morphological awareness could be taught as an extension of phonological instruction. In addition, morphemic analysis of an unfamiliar word can provide clues as to its meaning. Knowledge of derivational and inflectional affixes support comprehension of connected text by indicating the role of a word within a sentence, and how it might relate to the other words around it. Perhaps it is more precise to say that morphological instruction sits at the junction of code-focused and meaning-focused instruction, and could serve to bridge these two pedagogical approaches.

Researchers now generally agree that some balance between code-focused and meaning-focused instruction is necessary for successful literacy acquisition. However, this instructional balance is not “one size fits all.” Research has demonstrated an interaction between child-level factors and instructional strategies: the balance of instruction likely to lead to the greatest growth in reading depends in part on each child’s language and literacy proficiency. For instance, 1st graders with poor initial word reading skills have been shown to benefit more from explicit code-focused instruction than their more advanced peers (Connor et al., 2004).

Yet it remains unknown which students may benefit most from morphology instruction, or which aspects of morphology teachers might target at a given grade or skill-level. In Chapter III, Study 2A demonstrates that kindergarteners perform significantly better on compound morphological awareness items than on derivations, a difference that is not present in the older grades. Should a kindergarten teacher then assess a student’s knowledge of compounding, and use this information to differentiate instruction, either by teaching more about compound words or advancing to affixes? Along these same lines, the bilingual findings of Study 2B suggests that children’s home language background interacts with their morphological awareness to influence reading skill. For the highly proficient, balanced dual first-language learners in this study, differences in reading were best explained by children’s awareness of morphemic structures that were not reinforced by their home language. The logical implication is that teachers may be able to support their bilingual learners by giving them opportunities to practice with morphemic structures that are less familiar. However, it is not yet known if these findings are generalizable to a broader sample of bilinguals who are not highly proficient in both of their languages. As little is known about how child-level factors, such as vocabulary knowledge, reading skill, and home language background, might influence the efficacy of morphological instruction, this is an area ripe for future inquiry.

Strengths and Limitations

This dissertation presents several methodological strengths. First, the overall conclusions of this dissertation are informed by a complementary brain-behavior approach that yielded converging evidence across two different neuroimaging methodologies. Each dissertation study had a relatively large sample size, particularly in the context of prior developmental research, and participants were drawn from multiple geographic locations. In particular, Study 2 analyzed data from 340 children living in two cities on opposite sides of the country. Participants across all three studies were extremely diverse in terms of their language backgrounds, multilingual exposure, and reading ability, all of which may increase our confidence in the generalizability of the findings.

However, there are important limitations of this sample as well. Participants largely came from high-SES homes, with highly educated parents. These samples are thus not representative of the United States population. Likely related to this relative educational privilege, participants across all three studies boasted mean vocabulary and oral comprehension standard scores between 112-118, a full standard deviation above the norm. This is a critical caveat in a dissertation focused on the role of language proficiency in learning to read. Furthermore, bilingual participants were highly proficient dual first-language learners, which is also not representative of the majority of bilingual children in the United States (although it does reflect the face of bilingualism in many other parts of the world). Additional research is needed among more representative samples before generalizing the conclusions of this dissertation more broadly.

Conclusion

The three studies in this dissertation aim to answer questions that have long intrigued researchers and educators: How does spoken language lay the foundation for learning to read, and how do these mechanisms vary across diverse learners? The results represent an important step towards understanding the role of spoken language proficiency, and morphological awareness more specifically, in developing a proficient reading brain. Taken together, these three studies further our theoretical conceptions of the neurobiology of literacy, the role of word knowledge in reading success, and the variability in neurocognitive mechanisms across diverse learners. It is my hope that these findings may prompt further research into the brain bases of spoken language processing in typical and impaired readers, and push towards the inclusion of more explicit morphological instruction, starting in the first years of schooling. As young learners in the United States become increasingly diverse, this research provides an important step towards understanding how to support children as they learn to read.

Appendices

Appendix A

fMRI Task Stimuli

Table A.1 Auditory word matching stimuli

	Word1	Word2	Condition	Word1	Word2	Condition
1	pants	pants	Match	hole	mop	Non-Match
2	pumpkin	pumpkin	Match	helmet	napkin	Non-Match
3	king	king	Match	mirror	glasses	Non-Match
4	witch	witch	Match	lizard	closet	Non-Match
5	picture	picture	Match	mailbox	toothpaste	Non-Match
6	tie	tie	Match	sun	wood	Non-Match
7	turkey	turkey	Match	tongue	bone	Non-Match
8	bucket	bucket	Match	mouse	sock	Non-Match
9	gift	gift	Match	cherry	puzzle	Non-Match
10	thumb	thumb	Match	mat	hose	Non-Match
11	bird	bird	Match	wrist	nail	Non-Match
12	palm	palm	Match	leaf	joke	Non-Match

Table A.2 Visual word matching stimuli

	Word1	Word2	Condition	Word1	Word2	Condition
1	number	number	Match	jar	bow	Non-Match
2	chicken	chicken	Match	tool	shell	Non-Match
3	brick	brick	Match	bear	shark	Non-Match
4	wolf	wolf	Match	skate	snail	Non-Match
5	tiger	tiger	Match	rabbit	pencil	Non-Match
6	tent	tent	Match	sink	clip	Non-Match
7	pot	pot	Match	green	house	Non-Match
8	plate	plate	Match	dog	mug	Non-Match
9	swing	swing	Match	garbage	bedroom	Non-Match
10	whale	whale	Match	game	road	Non-Match
11	washer	washer	Match	boat	salt	Non-Match
12	cat	cat	Match	birthday	chicken	Non-Match

Appendix B

Early Lexical Morphology Measure (ELMM)

Administration: Read instructions and 40 test items to the child. If child provides incorrect or no response, record verbatim. Also note self-corrections.
Feedback: Provide feedback only on training. Tester can repeat each item once if requested.
Ceiling: 10 incorrect in a row.
Suggested prompts: How should we finish that sentence? Do you want to take your best guess?

Instructions: We're going to play a game with sentences. I will say a word, and then you are going to use part of that word to help me finish a sentence. Ready?

Training:

A. Friendly She is my best ______________________. Friend E

If correct: Right! We can take part of the word "friendly," and turn it into the word "friend" to finish that sentence. Let's try another one. **Proceed to Item 1.**

If incorrect: Remember, we're going to use the word I say to finish the sentence. If I say "friendly," we can use part of that word to make "friend." She is my best *friend*. Let's try another. **Go to training item B.**

B. Playful Let's go outside and ______________________. Play E

If correct: Right! We can take part of the word "playful," and turn it into the word "play" to finish that sentence. Let's try another one. **Proceed to Item 1.**

If incorrect: Remember, we're going to use the word I say to finish the sentence. If I say "playful," we can use part of that word to make "play." Let's go outside and *play*. Let's try another one. **Proceed to Item 1.**

Test items 1-40. No feedback.

1.	**Foggy**	On some mornings, you can see _________________.	Fog	E
2.	**Runner**	My sister and I went on a _________________.	Run	E
3.	**Teamwork**	This weekend, my dad has to _________________.	Work	E
4.	**Football**	Ouch! You stepped on my _________________.	Foot	E
5.	**Quickly**	That lion was _________________.	Quick	E
6.	**Teaspoon**	I eat my soup with a _________________.	Spoon	E

7.	**Sidewalk**	The baby is learning how to ________________.	Walk	E
8.	**Noisy**	Did you hear that ________________?	Noise	E
9.	**Colorful**	That flower is such a pretty _____________________.	Color	E
10.	**Classroom**	Go upstairs and clean your _____________________.	Room	E
11.	**Stroller**	Would you like to go for a _____________________?	Stroll	E
12.	**Sensitive**	He wasn't making any ____________________.	Sense	E
13.	**Awesome**	She looked at the ocean with _____________________.	Awe	E
14.	**Computer**	The distance from here to Jupiter is hard to ____________.	Compute	E
15.	**Personality**	George Washington was a famous ________________.	Person	E
16.	**Careful**	Those glasses look breakable! Handle them with ___________.	Care	E

You are doing a great job! Let's keep going. Remember, we're going to use part of the word I say to finish the sentence

17.	**Blueberry**	My favorite shirt is ________________.	Blue	E
18.	**Election**	How many women did they ________________?	Elect	E
19.	**Backyard**	I forgot my jacket, so I have to go ________________.	Back	E
20.	**Argument**	My coach told me not to ________________.	Argue	E
21.	**Rainbow**	I like to go outside in the ________________.	Rain	E
22.	**Breakfast**	It's time to take a ________________.	Break	E
23.	**Correction**	How many mistakes did the teacher ________________?	Correct	E
24.	**Raincoat**	Before I play in the snow, I put on my ________________.	Coat	E
25.	**Curiosity**	Cats are always ________________.	Curious	E
26.	**Breathe**	In the winter, sometimes you can see your _____________.	Breath	E
27.	**Height**	That box is too ________________.	High	E
28.	**Seaweed**	The mermaid lives in the ________________.	Sea	E
29.	**Necklace**	Let's tie it together with ________________.	Lace	E
30.	**Discussion**	What did she want to ________________?	Discuss	E

31.	**Vacation**	The police told us we have to _______________.	Vacate	E
32.	**Warmth**	At night, my room gets too _______________.	Warm	E
33.	**Combination**	Which colors should the painter _______________?	Combine.	E
34.	**Afternoon**	I'm reading right now, but we can play _____________.	After	E
35.	**Elasticity**	That rubber band feels _______________.	Elastic	E
36.	**Length**	The river is very _______________.	Long	E
37.	**Somebody**	My dog has big ears and a little _______________.	Body	E
38.	**Decision**	Which game should we play? I can't _______________.	Decide	E
39.	**Strengthen**	Fire fighters have to be really _______________.	Strong	E
40.	**Remarkable**	Did you hear his _______________?	Remark	E

Total # incorrect: ________

Raw score: _________ / 40

Compounds	Derivations	
1. Rainbow / rain*	1. Foggy / fog††	16. Height / high*††
2. Football / foot*	2. Runner / run*†	17. Discussion / discuss††
3. Teaspoon / spoon*	3. Quickly / quick*	18. Vacation / vacate
4. Sidewalk / walk*	4. Noisy / noise*	19. Warmth / warm*†
5. Classroom / room*	5. Colorful / color*	20. Combination / combine†
6. Seaweed / sea*	6. Stroller / stroll	21. Elasticity / elastic
7. Blueberry / blue*	7. Sensitive / sense†	22. Length / long*
8. Backyard / back*	8. Computer / compute	23. Decision / decide
9. Teamwork / work*	9. Personality / person*	24. Strength / strong*
10. Breakfast / break*	10. Careful / care*†	25. Remarkable / remark††
11. Raincoat / coat*	11. Election / elect††	
12. Somebody / body*	12. Argument / argue*	
13. Afternoon / after*	13. Correction / correct*	
14. Necklace / lace	14. Curiosity / curious	
15. Awesome / awe	15. Breathe / breath*†	

Note. *Early acquired root word. †Item modified from Goodwin et al.'s (2012) Extract the Base task. ††Verbatim item in Goodwin et al.'s (2012) Extract the Base task.

Appendix C

fNIRS Methods

Figure C.1 *fNIRS cap and probe configuration*

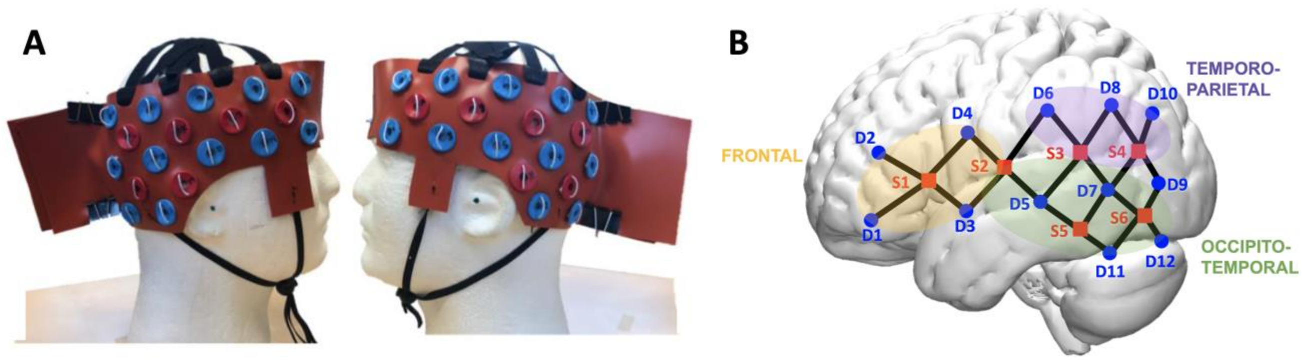


Figure C.2 *Morphological awareness task design*

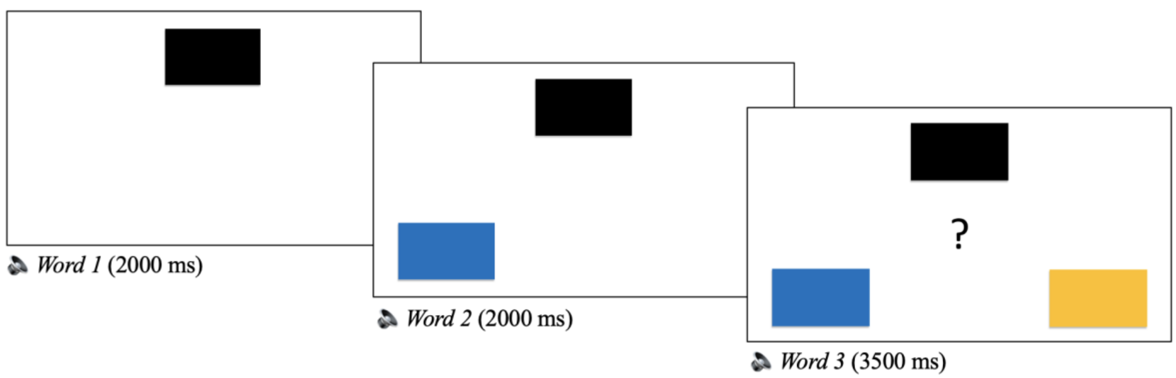


Table C.1 *Morphological awareness task stimuli*

Word1	**Word2 (match)**	**Word3 (distractor)**	**Condition**
airport	airplane	area	Roots
human	woman	lemon	Roots
motorcycle	bicycle	recycle	Roots
car	carseat	carpet	Roots
teammate	classmate	animate	Roots
caring	careful	carrot	Roots
pencil	penpal	penguin	Roots

camper	camping	camera	Roots
painter	painting	painful	Roots
end	weekend	friend	Roots
sunlight	flashlight	polite	Roots
teacup	teapot	T-rex	Roots
winning	winner	window	Roots
spaceship	battleship	friendship	Roots
eyebrow	eyelash	iPhone	Roots
something	somewhere	summer	Roots
disagree	dishonest	distance	Affixes
running	jumping	ceiling	Affixes
skiing	dancing	morning	Affixes
warmer	colder	finger	Affixes
teacher	doctor	closer	Affixes
laughing	joking	pudding	Affixes
cutest	coldest	forest	Affixes
dirty	muddy	coffee	Affixes
excitement	amazement	apartment	Affixes
heavy	sleepy	money	Affixes
reset	replay	reading	Affixes
walking	pulling	earring	Affixes
destroy	detach	dessert	Affixes
dancer	waiter	corner	Affixes
mistake	misspell	mister	Affixes
dislike	disobey	display	Affixes
laundry	laundry	bookshelf	Control
napkin	napkin	giggle	Control
blanket	blanket	popcorn	Control
number	number	taxi	Control
lady	lady	finish	Control
staple	staple	frosting	Control
textbook	textbook	maybe	Control
power	power	cartoon	Control
explore	explore	measure	Control
question	question	after	Control
paddle	paddle	decide	Control
minute	minute	children	Control
ground	ground	story	Control
country	country	dentist	Control
alarm	alarm	marker	Control
snowball	snowball	parrot	Control

Table C.2 *Estimated left hemisphere brain regions covered by the fNIRS probeset*

			MNI coordinates						MNI coordinates		
Source	Detector	Region	*x*	*y*	*z*	Source	Detector	Region	*x*	*y*	*z*
1	1	vIFG, MFG	-56	50	-17	4	7	SMG, STG, MTG, IPL	-56	-46	-2
1	2	MFG, dIFG	-53	49	-1	4	8	IPL, SMG, AG	-53	-43	17
1	3	vIFG, Precentral	-62	29	-14	4	9	MTG, AG, STG, SMG	-46	-59	1
1	4	dIFG, MFG	-59	33	5	4	10	AG, Precuneus, IPL, STG	-45	-53	15
2	3	Precentral, STG, IFG	-65	12	-11	5	5	MTG, STG	-67	-22	-26
2	4	IFG, Precentral, MFG	-62	17	8	5	7	MTG, STG	-63	-36	-23
2	5	Postcentral, STG, Precentral	-68	-4	-9	5	11	ITG, MTG, FG	-58	-40	-40
2	6	Precentral, Postcentral	-64	-1	11	6	7	MTG, STG, MOG, ITG	-55	-50	-21
3	5	STG, Postcentral, IPL, TTG	-67	-19	-6	6	9	MOG ITG, FG, MTG	-51	-54	-38
3	6	Precentral, Postcentral, IPL	-64	-16	14	6	11	MOG, MTG, ITG	-45	-63	-18
3	7	STG, SMG, IPL, Postcentral	-63	-33	-3	6	12	ITG, IOG, MOG, FG	-44	-64	-34
3	8	IPL, Postcentral, SMG	-60	-30	16						

Note. d: Dorsal; v: Ventral; IFG: Inferior Frontal Gyrus; MFG: Middle Frontal Gyrus; STG: Superior Temporal Gyrus; IPL: Inferior Parietal Lobule; MTG: Middle Temporal Gyrus; TTG: Transverse Temporal Gyrus; SMG: Supramarginal Gyrus; AG: Angular Gyrus; ITG: Inferior Temporal Gyrus; FG: Fusiform Gyrus; MOG: Middle Occipital Gyrus; IOG: Inferior Occipital Gyrus. Regions are reported in the order of greatest probability for each channel. Each channel has a right hemisphere homologue.

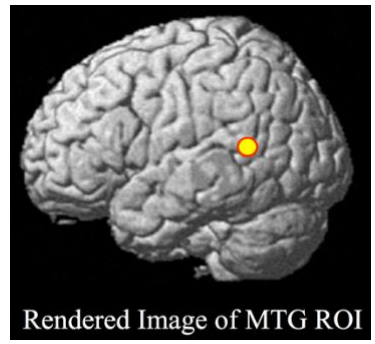
Appendix D

Study 1 Supplementary Information

Table D.1 *Regression explaining correlation between speech-related and print-related activity in MTG region of interest*

Predictor	β	*t*(62)	*p*
Scanner	-.17	-1.26	.211
Age	-.14	-1.05	.297
Gender	.05	.38	.703
Maternal education	-.06	-.44	.662
Word reading (LWID)	.12	1.56	.124

Note. The model does not account for a significant amount of variance, $R^2 = 0.08$, $F(5,62) = 1.13$, $p = .357$.



Language and Literacy Skills of Longitudinal Participants (*N* = 49)

Table D.2 *Standard scores of language and literacy skills in 1st grade*

Construct	Mean (SD)
Age	7.13 (0.32)
Gender	24 boys / 25 girls
Receptive vocabulary	119.70 (15.56)
Oral comprehension	112.02 (13.26)
Morphological awareness [a]	20.32 (4.37)
Phonological awareness [b]	23.49 (6.53)
Letter/word reading	107.22 (18.40)
Reading comprehension	104.98 (14.08)

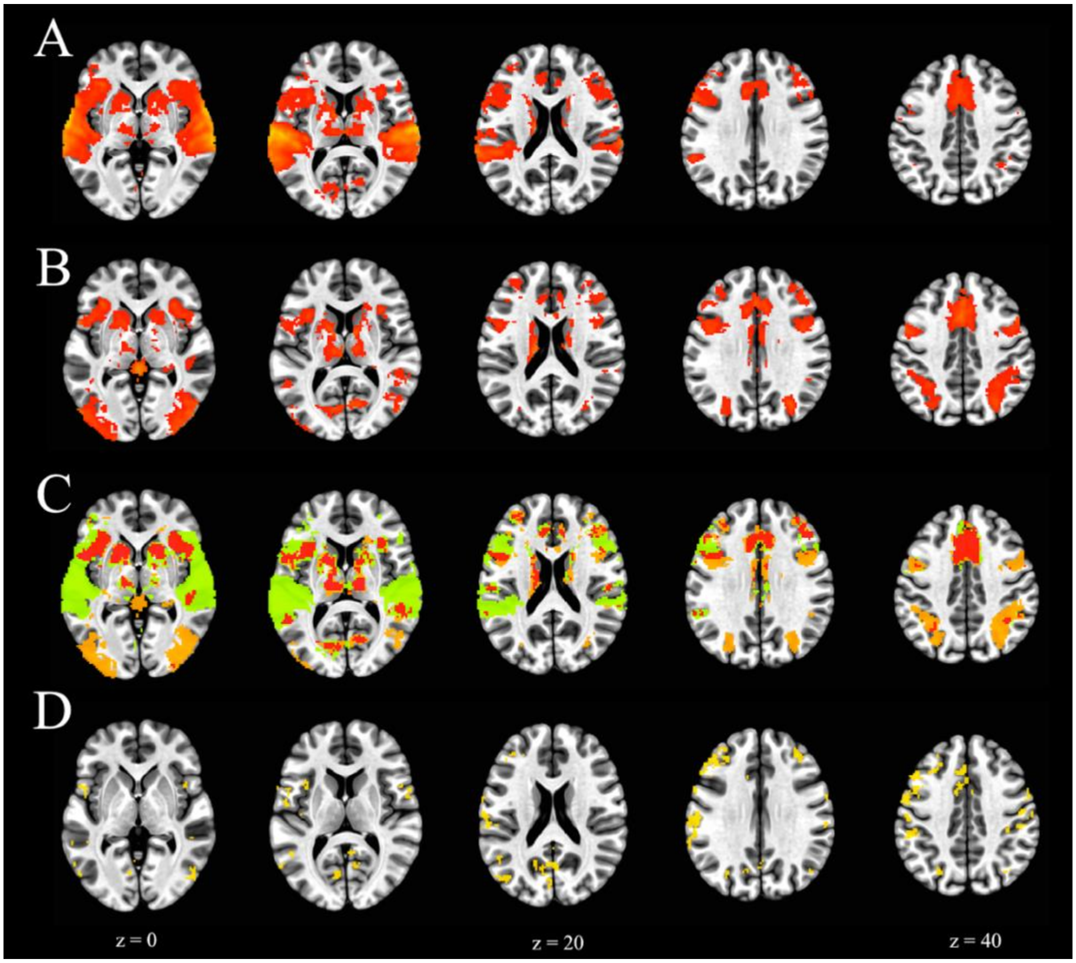
Note. [a] Raw score out of 25. [b] Raw score out of 34.

Table D.3 *Growth in language and literacy raw scores between kindergarten and 1st grade*

	Kindergarten	1st grade	*t*
Receptive vocabulary [a]	118.87 (20.84)	140.36 (20.23)	10.63***
Oral comprehension [b]	13.72 (3.81)	16.94 (3.89)	9.09***
Letter/word reading [c]	19.23 (10.49)	43.19 (12.64)	16.61***
Reading comprehension [d]	11.08 (5.02)	24.38 (6.64)	14.93***

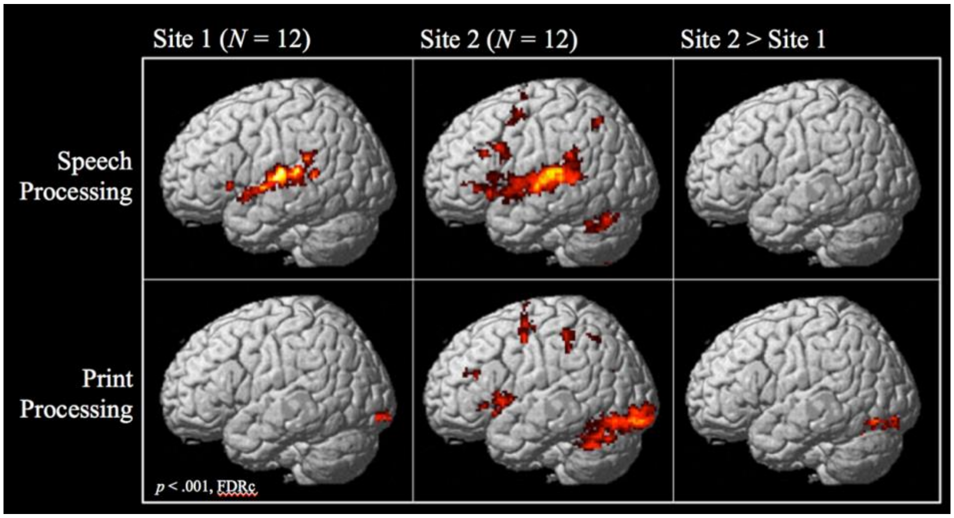
Note. N = 49. Raw scores presented. *T* statistic represents the difference between children's raw score in 1st grade vs. Kindergarten. *** $p < .001$. [a] Peabody Picture Vocabulary Test (PPVT-4). [b] WJ-IV Oral Comprehension subtest. [c] WJ-IV Letter-Word Identification. [d] WJ-IV Passage Comprehension.

Figure D.1 *Additional visualizations of activation for print and speech*



Note. Additional slices of A. Speech processing > Rest; B. Print processing > Rest; C. Print-speech convergence, and D. Voxel-wise correlation.

Figure D.2 *Comparison of fMRI results from Site 1 and Site 2*



Study 2 Supplementary Information

Table D.4 *Study 2A participants' language background by grade*

	English monolinguals		Spanish-English bilinguals		Chinese-English bilinguals		Other home language	
	N	%	*N*	%	*N*	%	*N*	%
Pre-K – K (*N* = 68)	26	38.2	16	23.5	26	28.2	0	-
1st grade (*N* = 137)	60	43.7	34	24.8	38	29.9	5	3.6
2nd grade (*N* = 88)	33	27.5	30	34.1	21	23.9	4	4.5
3rd grade (*N* = 47)	21	44.7	13	27.7	3	27.7	0	-

Table D.5 *Hierarchical regression explaining word reading in K-1st graders*

	β	*t*	*p*	*R*	R^2	ΔR^2
Step 1				.528	.268	
Constant		-3.58	<.001			
Age	.51	8.14	<.001			
Bilingual status	.22	3.57	<.001			
Maternal education	.06	0.95	.345			
Step 2				.734	.526	.259
Constant		-4.28	<.001			
Age	.30	5.04	<.001			
Bilingual status	.24	4.28	<.001			
Maternal education	.04	0.79	.430			
Vocabulary	.09	1.35	.179			
Phon. awareness	.52	9.58	<.001			
Step 3				.764	.569	.045
Constant		-2.50	.013			
Age	.19	3.17	.002			
Bilingual status	.27	5.13	<.001			
Maternal education	.03	0.66	.508			
Vocabulary	.03	0.45	.652			
Phon. awareness	.41	7.16	<.001			
Morph. awareness	.31	4.44	<.001			

Note. $N = 190$. Final model explains significant variance in word reading, $F(6,184) = 42.87$, $p <.001$

Table D.6 *Hierarchical regression explaining word reading in 2nd-3rd graders*

	β	*t*	*p*	*R*	R^2	ΔR^2
Step 1				.437	.171	
Constant		-0.33	.745			
Age	.30	3.76	<.001			
Bilingual status	.10	1.18	.239			
Maternal education	.31	3.78	<.001			
Step 2				.767	.571	.397
Constant		-1.40	.164			

	β	*t*	*p*	*R*	R^2	ΔR^2
Age	.11	1.79	.077			
Bilingual status	.08	1.35	.179			
Maternal education	.08	1.31	.194			
Vocabulary	.25	3.59	<.001			
Phon. awareness	.58	8.99	<.001			
Step 3				.797	.617	.047
Constant		-0.83	.407			
Age	.07	1.22	.225			
Bilingual status	.12	1.99	.049			
Maternal education	.06	1.02	.309			
Vocabulary	.12	1.70	.091			
Phon. awareness	.49	7.67	<.001			
Morph. awareness	.30	3.96	<.001			

Note. $N = 127$. Final model explains significant variance in word reading, $F(6,121) = 35.12$, $p < .001$.

Table D.7 *Hierarchical regression explaining reading comprehension in K-1st graders*

	β	*t*	*p*	*R*	R^2	ΔR^2
Step 1				.494	.244	
Constant		-3.10	.002			
Age	.50	7.56	<.001			
Bilingual status	.12	1.83	.070			
Maternal education	.07	1.10	.273			
Step 2				.861	.741	.496
Constant		-1.01	.313			
Age	.05	1.00	.321			
Bilingual status	-.04	-0.87	.388			
Maternal education	-.01	-0.13	.894			
Vocabulary	.10	1.97	.051			
Phon. awareness	.10	1.95	.052			
Single word reading	.74	13.03	<.001			
Step 3				.864	.746	.005
Constant		-0.44	.664			
Age	.02	0.42	.672			
Bilingual status	-.02	-0.40	.691			
Maternal education	-.01	-0.15	.881			
Vocabulary	.08	1.59	.113			
Phon. awareness	.08	1.50	.135			
Single word reading	.70	11.95	<.001			
Morph. awareness	.11	1.88	.062			

Note. $N = 181$. Final model explains significant variance in reading comprehension, $F(7, 174) = 73.00$, $p < .001$, but is not significantly better than the 2nd model.

Table D.8 *Hierarchical regression explaining reading comprehension in 2nd-3rd graders*

	β	*t*	*p*	*R*	R^2	ΔR^2
Step 1				.442	.195	
Constant		-0.31	.759			
Age	.31	3.84	<.001			
Bilingual status	-.08	-0.92	.358			
Maternal education	.30	3.62	<.001			
Step 2				.815	.664	.469
Constant		-0.97	.336			
Age	.03	0.52	.606			
Bilingual status	-.07	-1.29	.200			
Maternal education	.04	0.62	.537			
Vocabulary	.26	3.95	<.001			
Phon. awareness	.07	0.92	.360			
Single word reading	.57	6.49	<.001			
Step 3				.835	.698	.034
Constant		-0.58	.562			
Age	.01	0.14	.890			
Bilingual status	-.03	-0.63	.533			
Maternal education	.03	0.49	.625			
Vocabulary	.18	2.71	.008			
Phon. awareness	.06	0.80	.426			
Single word reading	.46	5.17	<.001			
Morph. awareness	.27	3.61	<.001			

Note. N = 124. Final model explains significant variance in reading comprehension, $F(7, 117) = 38.63$, $p < .001$.

Table D.9 *Post-hoc regression explaining reading comprehension from morphology X language group interaction, not including word reading*

Reference group: Spanish bilinguals					Reference group: Chinese bilinguals				
	β	*t*	*p*			β	*t*	*p*	
Constant	-1.52	-3.31	.001	**	Constant	-1.24	0.43	.005	**
Age	0.19	3.18	.002	**	Age	0.19	3.18	.002	**
Maternal education	0.09	2.02	.045	*	Maternal education	0.09	2.02	.045	*
Vocabulary	0.28	4.25	<.001	***	Vocabulary	0.28	4.25	<.001	***
LG: Chinese	0.28	2.62	.010	*	LG: Spanish	-0.28	-2.62	.010	*
LG: English	-0.00	-0.01	.991		LG: English	-0.28	-2.80	.006	**
Derivations	0.10	0.84	.401		Derivations	0.31	2.71	.007	**
Compounds	0.34	2.74	.007	**	Compounds	0.06	0.57	.572	
Chinese * Derivations	0.22	1.42	.158		Spanish * Derivations	-0.22	-1.42	.158	
English * Derivations	0.48	3.01	.003	**	English * Derivations	0.26	1.69	.092	
Chinese * Compounds	-0.28	-1.77	.079		Spanish * Compounds	0.28	1.77	.079	
English * Compounds	-0.27	-1.71	.090		English * Compounds	0.01	0.05	.964	

Note. LG = Language Group. $F(11, 185) = 38.06$, $p < .001$, adjusted $R^2 = 0.68$.

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