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Brain bases of morphological awareness and longitudinal word reading outcomes

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ABSTRACT

Children's spoken language skills are essential to the development of the "reading brain," or the neurocognitive systems that underlie successful literacy. Morphological awareness, or sensitivity to the smallest units of meaning, is a language skill that facilitates fluent recognition of meaning in print. Yet despite the growing evidence that morphology is integral to literacy success, associations among morphological awareness, literacy acquisition, and brain development remain largely unexplored. To address this gap, we conducted a longitudinal investigation with 75 elementary school children (5–11 years of age) who completed an auditory morphological awareness neuroimaging task at Time 1 as well as literacy assessments at both Time 1 and Time 2 (1.5 years later). Findings reveal longitudinal brain–behavior associations between morphological processing at Time 1 and reading outcomes at Time 2. First, activation in superior temporal brain regions involved in word segmentation was associated with both future reading skill and steeper reading gains over time. Second, a wider array of brain regions across the language network were associated with polymorphemic word reading as compared with broader word reading skill (reading both simple and complex words). Together, these findings reinforce the importance of word segmentation skills in learning to read and highlight the importance of considering complex word reading skills in building comprehensive neurocognitive models of literacy. This study fills a gap in our knowledge of how processing meaningful units in speech may help to explain differences in children's reading development over time and informs

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ongoing theoretical questions about the role of morphology in learning to read.

Introduction

Learning to read requires children to connect their spoken language to print. Specifically, a child must learn to link units of sound (phonemes) and units of meaning (morphemes) to written words (Perfetti & Hart, 2002). Children learn to attend to word sounds and meanings long before they begin to learn to read, building a complex neurocognitive system for language processing. Although we know from behavioral research that spoken language skill predicts future reading outcomes (Melby-Lervåg, 2012; Snowling, 2005), less is known about the underlying brain mechanisms that connect spoken word processing to reading. Furthermore, most of the existing longitudinal studies have focused on brain bases of phonological processing, or sensitivity to word sounds, in relation to future reading (Łuniewska et al., 2019; Maurer et al., 2009; Wang et al., 2020, 2021). Yet the ultimate goal of reading is to extract meaning from print. This study fills a gap in our knowledge of how processing *meaningful units* of spoken words may help to explain differences in children's reading development over time. We examined associations between children's brain activations during an auditory lexical morphology task at Time 1 and word reading outcomes 1.5 years later at Time 2.

The role of morphology in learning to read

Learning to read requires an understanding of how units of sound and meaning combine to create words (Perfetti & Hart, 2002). Across languages, fluent reading is typically considered *morphophonological* (Frost, 2012). For instance, English is alphabetic, and sounds map onto letters with relative consistency. However, word spellings often preserve units of meaning despite changes in pronunciation (e.g., in *heal* vs. *health*). As children learn to read, they first learn to attend to small grain sizes (mapping between graphemes and phonemes) before learning to recognize larger units of print (Ehri, 2005, 2014).

All words consist of one or more meaningful units called *morphemes.* Morphological awareness refers to implicit sensitivity to (or explicit knowledge of) these meaningful units and how they can be combined. There has been a surge of ''theoretical advocacy" (Levesque & Deacon, 2022) for the role of morphology in models of reading development. The *Reading Systems Framework* (Perfetti & Stafura, 2014) suggests a dual role of morphology in reading and understanding connected text; it situates morphology as a component of the lexicon as well as an element of a reader's broader linguistic system that facilitates comprehension processes. At the single word level, *binding agent theory* (Kirby & Bowers, 2017) posits that morphology creates a bridge among the phonological, semantic, and orthographic constituents of words, strengthening the connections among them.

Yet although it is theoretically principled that morphology should contribute to successful reading development, the predictive power of morphological awareness has been somewhat more elusive. Particularly in contrast to phonological awareness, which is typically an extremely powerful predictor of early word reading skill in alphabetic languages such as English, adding morphological awareness to statistical models may predict an additional 2% to 4% of variance among young readers (e.g., Desrochers et al., 2018; Marks et al., 2022). Furthermore, although morphological awareness makes a direct contribution to reading morphologically complex words (e.g., *un-in-habit-able*), the contribution to broader word reading skill may be less pronounced (Levesque & Deacon, 2022). Thus, there is a challenge in aligning theoretical frameworks highlighting morphology as a key to skilled word reading with existing behavioral evidence, particularly in early grades. The current study took a novel neurocognitive approach to understanding morphological processes in reading development. We explored whether brain function for processing units of meaning in spoken words in elementary school children may help to explain a mechanistic role of morphology in future reading outcomes.

Spoken word processing and reading development over time

As children learn to read, they integrate their oral language skills with their developing knowledge of print. In the brain, this results in a network of overlapping cortical regions that process both spoken and written words (Rueckl et al., 2015). The emergence of the reading brain is initially driven by children's oral language proficiency (Frost et al., 2009; Jasińska et al., 2021; Marks et al., 2019; Preston et al., 2011). Kindergarteners' vocabulary knowledge, oral comprehension, and morphological awareness predict the amount of overlap between their spoken word processing and written word processing; the amount of overlap (also known as print–speech convergence) in kindergarten in turn predicts reading outcomes in first grade (Marks et al., 2019). Among 6- to 10-year-olds, print–speech convergence predicts reading outcomes 2 years later (Preston et al., 2016). In sum, the network of brain regions involved in spoken word processing becomes the foundation of the reading network. This framework lays the foundation for examining children's strengthening relations among specific language skills, literacy, and their neural organization for learning to read.

Phonological processing

The majority of brain research into oral language processing and reading outcomes has focused on fine-grained phonology-related processes as measured with sound discrimination or rhyme judgment tasks. The neural bases of phonological processing during infancy have been linked to reading years later; infants' responses to subtle differences in speech sounds, measured with EEG, are associated with their prereading skills at school entry (Guttorm et al., 2010) as well as reading in second grade (Leppänen et al., 2011). Similarly, electrophysiological responses during phonological processing in kindergarten help to predict reading outcomes in second, third, and fifth grades (Maurer et al., 2009).

As children become more proficient in their sound-to-print mapping skills, the decoding process becomes increasingly automated, allowing readers to focus on larger units of print (Ehri, 2005). As the neurobiological mechanisms underlying phonological processes become more automated (Yu et al., 2018), they are also less predictive of reading abilities as children become progressively more reliant on larger morphophonological word segments (Wang et al., 2021). For instance, 6-year-olds' brain activations when processing words with shared onsets (e.g., *coat–cup*) and rhymes (e.g., *wide–ride*) predicted their reading outcomes 1.5 years later at age 7.5 (Wang et al., 2020). Wang and colleagues (2021) also found preliminary evidence suggesting that functional brain connectivity at 7.5 years of age during rhyme processing—but not during onset processing—may predict reading at age 9. However, even rhyme processing was less robust at 7.5 years than at earlier ages in predicting reading outcomes. This evidence suggests that the measurement units in neurodevelopmental studies of reading should progress from phonological to morphophonological for better alignment with children's advancing literacy skills. The current study begins to fill this gap by examining brain activations during a morphological processing task and their relation to future reading outcomes.

Morphological processing

Advanced literacy skills involve processing morphophonological units, yielding rapid recognition of meaning (Carlisle & Kearns, 2017). Yet in comparison with the depth of knowledge of phonological processes in the brain and their relation to reading, much less is known about morphological processing. Still, a handful of studies demonstrate brain–behavior associations between auditory morphological processing and reading skill. Brain activations during an auditory morphological awareness task were positively correlated with reading comprehension skill in children aged 6 to 11 years (Marks et al., 2021). Better readers showed greater engagement of key temporoparietal language regions, particularly when attending to word affixes such as *un-*, *re-*, and *-ion*. Furthermore, neurocognitive mechanisms for morphological processing differ between children with and without reading impairments (Eggleston et al., 2023). Typical readers show greater engagement across the reading network when processing affixes (e.g., *friend-LY*) as compared with word roots (e.g., *girl-FRIEND, FRIEND-ship)*. In contrast, children with dyslexia fail to engage key reading regions when processing affixes, which are less semantically transparent and more challenging to segment (Eggleston et al., 2023). Together, this handful of studies suggests that the brain bases of processing morphemes in speech are associated with children's concurrent reading skill.

Still less is known about the neurocognitive mechanisms that may support longitudinal associations between morphological awareness and the reading brain. One prior study found that Finnish preschoolers' brain activations during a morphological processing task were not significantly associated with first grade reading (Louleli et al., 2021). The current study probed this question further by examining morphological processing and word reading in later elementary school, when readers are learning to recognize larger sublexical units. We offer a longitudinal inquiry into lexical morphological processing in English-speaking children with functional near-infrared spectroscopy (fNIRS).

The current study

This study examined the brain bases of auditory morphological processing and their relation to longitudinal reading outcomes. We focused on elementary school readers (5–11 years of age), spanning a wide range of literacy skill. This cross section captures readers relying on effortful sound-to-letter mapping as well as those with sophisticated recognition of larger orthographic units (Arredondo et al., 2015; Ehri, 2014). A total of 75 children completed behavioral language and literacy assessments and an auditory lexical morphology task during fNIRS neuroimaging at Time 1 as well as standardized literacy assessments 1.5 years later at Time 2. These time points span a critical period of literacy development when children rapidly improve in their word reading skills.

Our research question asked the following: Are the neurocognitive mechanisms that support morphological processing in spoken language associated with future reading? We hypothesized that children's engagement of the perisylvian language network during morphological awareness tasks administered at Time 1, specifically left inferior frontal, superior and middle temporal, and parietal regions, would be associated with children's reading development 1.5 years later at Time 2. We also hypothesized that we would observe stronger or more extensive brain–behavior associations with a more proximal measure of polymorphemic word reading and visual morphological awareness when compared with a standardized broader word reading assessment.

Method

Participants

A total of 75 monolingual English-speaking children (36 male and 39 female) participated in this study. At Time 1, children's average age was 8.33 years (*SD* = 1.67, range = 5–11). Of these participants, 20% were in kindergarten, 35% were in first or second grade, 30% were in third or fourth grade, and 15% were in fifth or sixth grade. At Time 2, the average age was 9.87 years (*SD* = 1.69, range = 6–12). Participants' racial/ethnic background and level of familial education were determined by a parent or guardian questionnaire completed at Time 1. Regarding race/ethnicity, 59 (78.7%) participating children were White and 13 (17.3%) were multiracial or multiethnic. Two children (2.7%) identified as Black or African American, 1 child (1.3%) identified as Native American or Alaska Native. Onechild (1.3%) additionally identified as Hispanic while the remaining 74 were not Hispanic or Latino. On average, participants grew up in highly educated households with average educational attainment of 9.17 on an 11-point scale. The educational attainment of primary guardians on this scale ranged from having some associate's level or certificate training (5) to having a doctorate degree (11).

Procedure

Participants were recruited as part of a larger longitudinal study on multilingual language and literacy development. Children participated in two testing sessions separated by an average of 1.54 years (*SD* = 2.88 months, range = 13–26 months). Time 1 behavioral and fNIRS data were collected between March 2019 and February 2020 during an in-person testing session. Time 2 data were collected between December 2020 and August 2021 during the first full year of remote schooling due to the COVID-19 pandemic. Time 2 testing sessions were conducted using Zoom video conferencing software. All monolingual English-speaking children with usable neuroimaging data at Time 1 (described below) who returned for Time 2 data collection were included in the current study.

Neuroimaging measure at Time 1

Participants completed a 7.2-min auditory morphology task during fNIRS neuroimaging. During each task trial, participants heard three words in sequence and were asked to indicate which two words shared a meaningful component. During the *base* condition, two of the three words shared a base morpheme, whereas the third word was a distractor (e.g., *bedroom, classroom, mushroom*). The distractor contained the same syllable or word segment as the two words with a shared morpheme, but the segment did not function as a meaningful unit. During the *affix* condition, two of the words shared a prefix or suffix, whereas the third word was a distractor in which the shared unit did not function as a morpheme (e.g., *cutest, coldest, forest*). During the *control* condition, participants were presented with two words that matched in their entirety and one word that was different (e.g., *napkin, napkin, giggle*). This condition incurred activation associated with whole word processing but did not require any morphological decomposition or analysis. Analyses were conducted with base > control and affix > control contrasts. These contrasts subtract brain activations associated with auditory whole word processing, which is shared across all conditions, to identify activations unique to morphological processes, that is, decomposing and analyzing morphologically complex words.

Each condition included 16 trials separated into four blocks with 4 trials each (48 items total). The order of the second matching word and the distractor was randomized once across trials. The overall internal reliability of the imaging task was a = .859 (base condition: a = .716; affix condition: a = .719; control condition: a = .849). Because this task was entirely auditory, all distractors in the base and affix conditions were phonologically equivalent but may have had different spellings (e.g., *eyebrow, eyelash, iPhone*). Additional task details are available in Marks et al., (2022) and Sun, Marks, et al., (2022), and all task materials are publicly available in Sun, Zhang, et al., (2022).

Behavioral oral language measures

Vocabulary

Receptive vocabulary was assessed at both time points using the Peabody Picture Vocabulary Test (PPVT-5; Dunn, 2018). In this task, participants hear a word and are asked to choose from four pictures to identify the meaning of the word. The PPVT-5 has high overall reliability at α = .97 (Dunn, 2018).

Phonological awareness

Phonological awareness was assessed using the Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP-2; Wagner et al., 2013). In this task, children hear a word and are asked to remove a unit of sound to make a new word (e.g., say *tiger* without saying */g/* [tire]). This task starts by asking children to remove whole syllables and progresses to the single phoneme level. CTOPP-2 has high internal consistency reliability at α > .80 (Wagner et al., 2013).

Morphological awareness

Participants completed the Early Lexical Morphology Measure (ELMM; Marks et al., 2022), in which they are given a word (e.g., *friendly*) and are asked to complete a spoken sentence using part of that word (e.g., she is my best____[friend]). This measure is distinct from other existing measures of English morphological awareness (Carlisle, 2000; Goodwin et al., 2012) because it includes compound items (e.g., *backyard;* I forgot my jacket, so I have to go____[*back*]) in addition to derived words. ELMM has 40 items and a reliability coefficient of α = .93.

Behavioral reading measures

Standardized reading measures (Time 1 and Time 2)

Reading skills were assessed using the Letter–Word Identification (broad single word reading), Word Attack (pseudoword decoding), and Passage Comprehension (reading comprehension) subtests from the Woodcock–Johnson IV Tests of Achievement (Schrank et al., 2014). These assessments have test–retest reliability of .87, .78, and .85, respectively.

Polymorphemic word reading (Time 2 only)

The polymorphemic word reading task, administered over Zoom at Time 2 only, was developed to match the auditory morphological awareness fNIRS task from Time 1. This task was both a measure of complex word reading and a measure of visual morphological awareness. Three words appeared on the screen in sequence, and participants indicated which two words shared a meaningful unit via button press. This task included a base condition (e.g., *seafood, seaweed, season*) and an affix condition (e.g., *nearly, mostly, family*). Because this task was entirely visual, all distractors matched orthographically but may have had different pronunciations (e.g., *unlucky, unhappy, unicorn*). Stimuli were presented using JATOS (Just Another Tool for Online Studies) open-source software (Lange et al., 2015). Participants were sent a unique link and completed the task online while sharing their screen with the experimenter.

Word reading gain over time was calculated based on children's raw scores on the Letter–Word Identification assessment using the following equation: (n words read correctly at Time 2 − n words read correctly at Time 1) / length of time between Time 1 and Time 2 assessments. Because 2 participants were missing Time 1 word reading data and 1 participant was missing Time 2 word reading data, analyses with word reading gains were conducted with $N = 72$ participants.

Missing data

Missing data were minimal, ranging from 0% to 5.3% missingness for any given assessment. To maximize the sample included in fNIRS analyses, we imputed missing values in five measures: Time 1 vocabulary (2 missing), Time 1 broad word reading (2 missing), Time 1 phonological awareness (1 missing), Time 2 broad word reading (1 missing), and Time 2 polymorphemic word reading (4 missing). Multiple imputation was performed using the *aregImpute* function of "Hmisc" (Version 4.8-0) in R. Ten values were imputed and averaged to replace the missing data. Imputed values were not used to calculate word reading gains over time.

Neuroimaging acquisition and analysis

fNIRS data were collected using a TechEN CW6 system and a custom probe set that targeted the perisylvian language network. We used prior literature to identify inferior frontal and temporoparietal language regions and used the international 10–10 system to build silicone headbands with mounted sources and detectors corresponding to these regions. The fNIRS probe set included 12 near-infrared light sources and 24 detectors spaced approximately 2.7 cm apart, yielding 46 data channels of source–detector pairings. These data channels were localized in MNI (Montreal Neurological Institute) stereotactic space using a combination of magnetic resonance imaging and photogrammetry optode registration (Hu et al., 2020). In the current study, we analyzed data from only 40 channels (20 per hemisphere) because the most ventral posterior three channels had the poorest signal-to-noise ratio, likely due to poor connection between the optodes and the scalp behind participants' ears as observed during data collection. A diagram of the fNIRS probe set and estimated regions covered by each channel are detailed in the online Supplementary material.

The probe set headband was positioned on each participant using the international 10–10 transcranial system (Jurcak et al., 2007). Trained experimenters measured the head circumference and identified the nasion, inion, Fpz, and left and right pre-auricular points. F7, F8, T3, and T4 were anchored to a specific source or detector. Cardiac signal was monitored in the frontal channels to ensure the quality of optode placement. fNIRS data were collected at a sampling frequency of 50 Hz at 690- and 830-nm wavelengths. Techen CW6 software signal-to-noise ratio minimum and maximum were set to the standard 80- to 120-dB range.

Each raw data file was trimmed to keep only 5 s of pre- and post-experimental task baseline data and downsampled to 2 Hz. Optical density data were converted to hemoglobin concentration change using the modified Beer–Lambert law. Each participant's hemoglobin concentration data were then analyzed using the NIRS Brain AnalyzIR Toolbox (Santosa et al., 2018), a MATLAB software. The canonical hemodynamic response function was modeled to peak 6 s after trial onset (Friston et al., 2007). General linear models (GLMs) were constructed with pre-whitening and robust least squares regression (Barker et al., 2013; Friston et al., 2007). We used an autoregressive filter combined with a weighted least squares estimation approach to eliminate the nonspherical 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 temporal and dispersion derivatives were added to the canonical hemodynamic response function as well as the discrete cosine transform matrix to account for signal drift over time. The single-participant GLMs yielded estimated individual-level regression coefficients for oxygenated hemoglobin (HbO) and deoxygenated hemoglobin signal for each condition and each channel. Each individual time series was visually inspected to ensure that no technical errors interfered with data acquisition before being included in a second-level model.

Group-level analyses were then conducted using linear mixed-effects models for each data channel, including participant as a random effect. Behavioral variables of interest (i.e., reading scores) were *z*-scored and included as interaction terms. Estimated group-level effects were extracted for each channel and contrast of interest and were plotted on the MNI 152 brain template using the previously digitized MNI coordinates. We present HbO analyses below, as fNIRS instruments capture the HbO signal with greater reliability and thus it accounts for a larger proportion of the signal (Gagnon et al., 2012). We present only the effects that survived false detection rate correction for multiple comparisons.

Results

Descriptive statistics of standardized language and reading measures repeated at both time points are presented in Table 1. Average scores fell in the high average range on spoken language measures

Table 1
Descriptive statistics at Time 1 and Time 2.

	Time 1		Time 2		
	M	SD	*M*	SD	*p*
Age	8.36	1.67	9.90	1.70	<.001
Vocabulary					
Raw	164.72	23.59	181.11	19.71	<.001
Standard	114.81	16.02	114.43	13.19	.876
Phonological awareness					
Raw	21.73	6.99	24.53	6.32	.011
Scaled	9.75	2.69	9.39	2.98	.448
Word reading					
Raw	47.30	15.26	56.55	11.79	<.001
Standard	103.30	19.20	104.60	19.45	.688
Pseudoword decoding					
Raw	18.76	6.21	21.79	5.08	<.001
Standard	105.51	15.46	103.96	14.96	.537
Reading comprehension					
Raw	27.00	8.11	32.30	6.68	<.001
Standard	99.66	16.32	98.58	15.95	.684

Note. Standard scores have a mean of 100 and a standard deviation of 15. Scaled scores have a mean of 10 and a standard deviation of 3.

and in the typical range for reading measures at both time points. Participants demonstrated expected growth between Time 1 and Time 2.

Given the context of COVID-19 and remote schooling during the time gap between Time 1 and Time 2, we also examined the associations among language, reading, and demographic factors at each time point. Notably, we observed a significant positive correlation between parental education and multiple measures of reading skill at Time 2 (e.g., bivariate correlation with word reading: $r = .30$, $t = 2.69$, $p = .009$) but not at Time 1 ($r = .08$, $t = 0.68$, $p = .498$). Put another way, children in higher socioeconomic status (SES) homes made greater gains in their reading skill during this period of remote schooling compared with their peers of relatively lower SES (i.e., correlation with change in Letter–Word Identification performance: $r = .27$, $t = 2.34$, $p = .019$). Because COVID was not the focus of this study, we accounted for this by controlling for the level of maternal education and time between Time 1 and Time 2 assessments in all behavioral and brain analyses. Partial correlations between oral language and reading scores are presented in Table 2.

Brain bases of auditory morphological processing

The auditory morphology task incurred widespread activation across bilateral language regions of the brain (Fig. 1). Children performed with relatively high task accuracy. Average performance was highest during the control condition ($M = .94$, SD = .13), followed by the base ($M = .83$, $SD = .13$) and affix ($M = .73$, SD = .19) conditions. Compared with whole word processing, the base morpheme condition (*bed<u>room</u>, class<u>room</u>*) incurred significantly greater engagement of the left ventral inferior frontal gyrus (vIFG), left middle temporal gyrus (MTG), and right superior temporal and supramarginal gyri (STG and SMG). The affix condition (*cut<u>est</u>, cold<u>est</u>*) incurred significantly greater left dorsal and ventral IFG and left STG activations as well as wider spread engagement of right temporoparietal regions. Direct comparison of the affix and base conditions revealed that processing affixes, which are smaller and more lexically abstract units, generally required greater engagement of the left IFG and bilateral STG. The base morpheme condition, in contrast, incurred greater activity in the left MTG, a hub of lexical processing.

Table 2
Partial correlations between Time 1 oral language and word reading and Time 2 reading outcomes.

		1	2	3	4	5	6	7	8	9	10
Time 1											
1	Vocabulary	–									
2	Phonological awareness	.35**	–								
3	Morphological awareness	.51***	.54***	–							
4	Word reading	.31**	.68***	.55***	–						
5	Pseudoword decoding	.27*	.73***	.54***	.84***	–					
6	Reading comprehension	.40***	.64***	.60***	.82***	.65***	–				
7	fNIRS task accuracy (auditory morphological awareness)	.27*	.38**	.41***	.43***	.36**	.44***	–			
Time 2											
8	Word reading	.30*	.67***	.44***	.89***	.76***	.80***	.39***	–		
9	Pseudoword decoding	.25*	.64***	.40***	.78***	.77***	.64***	.33**	.86***	–	
10	Reading comprehension	.40***	.58***	.44***	.75***	.64***	.77***	.39***	.82***	.72***	–
11	Polymorphemic word reading (visual morphological awareness)	.27*	.55***	.45***	.62***	.48***	.65***	.29*	.75***	.64***	.71***

Note. $N = 75$. Partial correlations control for age at Time 1, socioeconomic status, and time between assessments. fNIRS, functional near-infrared spectroscopy.
*$p < .05$.
**$p < .01$.
***$p < .001$.

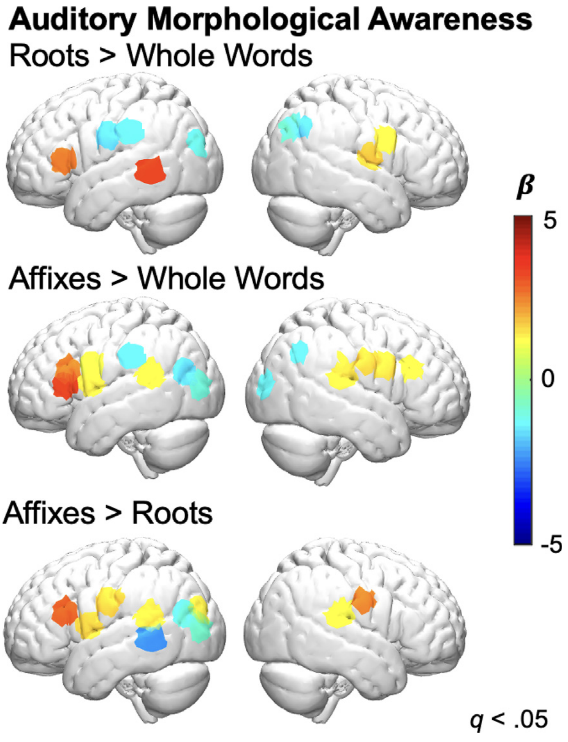

Fig. 1. Auditory morphological awareness condition contrasts.

Brain activations at Time 1 and word reading at Time 2

We then tested our hypothesis that brain activations during the morphology task at Time 1 were related to word reading outcomes at Time 2. We examined two dependent variables: broad reading skill as assessed with a standardized measure of word reading and a more proximal measure of polymorphemic word reading that was designed as a visual equivalent to the auditory morphological awareness task. To partial out the variance attributable to morphological processes as compared with other key literacy skills, phonological awareness and vocabulary knowledge were included as covariates. Although this study focused on word reading, an additional analysis examining reading comprehension outcomes at Time 2 is included in the Supplementary material.

Broad word reading skill

We modeled the main effects and interaction between task condition (base, affix, or whole word control) and children's Letter–Word Identification standard score at Time 2. Standard scores reflect children's word reading skills in relation to children of the same age. Standard scores of word reading, phonological awareness, and vocabulary at Time 1, SES, and length of time between Time 1 and Time 2 were included as covariates of no interest.

Greater brain activation in key language regions at Time 1 was associated with better reading skills 1.5 years later at Time 2 (Fig. 2). Engagement of the bilateral STG during base and affix processing was associated with higher Time 2 word reading standard scores, independent of reading ability at Time 1. Better readers at Time 2 also had more extensive activation across temporoparietal regions during the affix condition specifically, including left SMG and MTG and right posterior STG/angular gyrus. Statistical values for these longitudinal brain–behavior associations are detailed in Table 3. Power for each

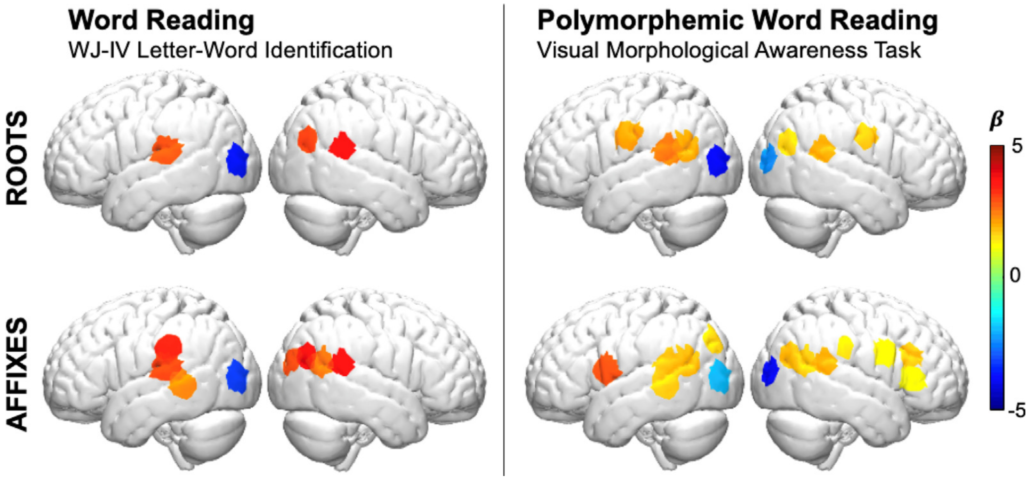

Fig. 2. Brain–behavior interaction between morphology condition and word reading outcome. WJ-IV, Woodcock–Johnson IV Tests of Achievement.

significant channel ranges from .68 in the right MTG/angular gyrus to .99 in the right STG, or upward of 68% power to detect a change at $p < .05$ in a one-sided t test (Santosa et al., 2018).

Polymorphemic word reading

Next, we examined the interaction between task condition and accuracy on the polymorphemic word reading task. This model also included word reading, phonological awareness, and vocabulary raw scores at Time 1, SES, and length of time between Time 1 and Time 2. Children's age at Time 1 was also included as a covariate of no interest because accuracy on the polymorphemic word reading measure was not age-normed. Results revealed that, like the measure of broader word reading skill, polymorphemic word reading at Time 2 was associated with greater brain activations in the bilateral STG for both conditions. Affix processing was also associated with more extensive temporal activation than the base condition, extending into the left MTG and right posterior STG. We also observed longitudinal brain–behavior associations in additional brain regions, namely the bilateral motor cortex during the base condition and the bilateral frontal regions during the affix condition. Power calculations for significant channels ranged from .55 in the left angular gyrus and right IFG to .99 in the left IFG.

The main effects of phonological awareness and vocabulary knowledge were consistent across both the broad word reading and polymorphemic word reading models. Phonological awareness was positively associated with activation in bilateral posterior STG, whereas vocabulary knowledge had a small but significant negative association with right posterior STG activation. Statistical values for these covariates are detailed in the Supplementary material.

Brain activations at Time 1 and word reading gains over time

Finally, we examined brain–behavior associations between auditory morphological processing at Time 1 and participants' gains on the standardized Letter–Word Identification assessment between Time 1 and Time 2. Word reading difference scores ranged from −2.93 (fewer words read correctly at Time 2) to 22.14, with an average of 6.10 additional words read per year (SD = 4.81). Participants who were missing this assessment at either time point were excluded from this analysis, leaving a sample of N = 72. This final GLM modeled the interaction between task condition and word reading gains, including age, phonological awareness, and vocabulary at Time 1 as well as SES as covariates of no interest. There were no significant positive brain–behavior associations during the base mor-

Table 3
fNIRS channels revealing significant brain-behavior interactions with T2 reading outcomes.

Channel		Regions	β	t	p	q	Power
Base Morphemes × Time 2 Broad Word Reading							
L	2.5	PostCG, STG, PreCG	2.88	3.23	.001	.017	.77
L	6.9	MOG, ITG, FG, MTG	−3.76	−3.63	<.001	.006	.87
R	3.5	STG, PreCG, IPL, TTG	3.78	4.47	<.001	.000	.99
R	4.7	SMG, STG, MTG, IPL	3.11	3.32	.001	.015	.80
Affixes × Time 2 Broad Word Reading							
L	2.5	PostCG, STG, PreCG	3.02	3.32	.001	.011	.80
L	2.6	PreCG, PostCG	3.36	3.71	<.001	.004	.89
L	5.5	MTG, STG	2.53	2.95	.003	.026	.68
L	6.9	MOG, ITG, FG, MTG	−3.24	−3.07	.002	.022	.72
R	3.5	STG, PostCG, IPL, TTG	3.95	4.55	<.001	<.001	.98
R	3.7	STG, SMG, IPL, PostCG	2.61	3.02	.003	.023	.70
R	4.7	SMG, STG, MTG, IPL	3.82	4.04	<.001	.001	.94
R	4.9	MTG, AG, STG, SMG	3.00	3.42	.001	.009	.82
Base Morphemes × Time 2 Polymorphemic Word Reading (visual morphological awareness)							
L	2.4	IFG, PreCG, MFG	2.26	3.64	<.001	.004	.87
L	3.5	STG, PostCG, IPL, TTG	2.63	4.56	<.001	<.001	.98
L	3.7	STG, SMG, IPL, PostCG	2.16	3.83	<.001	.002	.91
L	6.9	MOG, ITG, FG, MTG	−3.92	−5.60	<.001	<.001	.99
R	2.4	IFG, PreCG, MFG	2.06	3.29	.001	.009	.79
R	2.5	PostCG, STG, PreCG	2.09	3.51	<.001	.005	.85
R	4.7	SMG, STG, MTG, IPL	1.68	2.68	.008	.046	.58
R	6.9	MOG, ITG, FG, MTG	−2.38	−2.83	.005	.032	.63
Affixes × Time 2 Polymorphemic Word Reading (visual morphological awareness)							
L	1.3	Ventral IFG, PreCG	2.93	4.87	<.001	<.001	.99
L	3.5	STG, PostCG, IPL, TTG	2.02	3.32	.001	.012	.80
L	3.7	STG, SMG, IPL, PostCG	2.03	3.43	.001	.010	.83
L	4.10	AG, precuneus, IPL, STG	1.66	2.62	.009	.048	.55
L	5.5	MTG, STG	1.82	2.85	.004	.035	.64
R	1.1	Ventral IFG, MFG	−1.97	−2.66	.008	.048	.57
R	1.2	MFG, dorsal IFG	1.22	2.62	.009	.048	.55
R	1.3	Ventral IFG, PreCG	1.98	3.46	.001	.010	.84
R	1.4	Dorsal IFG, MFG	1.42	2.62	.009	.048	.55
R	2.6	PreCG, PostCG	1.64	2.83	.005	.035	.63
R	3.5	STG, PostCG IPL, TTG	2.09	3.30	.001	.012	.79
R	3.7	STG, SMG, IPL, PostCG	1.89	3.12	.002	.019	.74
R	4.7	SMG, STG, MTG, IPL	2.02	3.07	.002	.020	.72
R	6.9	MOG, ITG, FG, MTG	−3.95	−4.34	<.001	.001	.97

Note. Channels are notated as [source].[detector] pairings. Regions are reported in the order of greatest probability for each channel. q, Benjamini–Hochberg corrected p values; Power, Type II power calculation at α = .05. L, left hemisphere; R, right hemisphere; PostCG, postcentral gyrus; STG, superior temporal gyrus; PreCG, precentral gyrus; MOG, middle occipital gyrus; ITG, inferior temporal gyrus; FG, fusiform gyrus; MTG, middle temporal gyrus; IPL, inferior parietal lobule; TTG, transverse

pheme condition. In contrast, a larger difference score was associated with greater engagement of the left IFG, SMG, and MTG and the bilateral STG during affix processing (see Fig. 3 and Table 4). Power calculations for significant channels ranged from .52 in the left MTG to .97 in the left postcentral/angular gyrus.

Discussion

This study examined longitudinal brain–behavior associations between spoken word processing at Time 1 and reading outcomes at Time 2. A total of 75 elementary school readers (kindergarten through sixth grade) completed a morphological awareness task during fNIRS neuroimaging in which they heard three words and determined which two shared either a base morpheme (e.g., *classroom, bedroom, mushroom*) or an affix (*dancer, waiter, corner*). Activations in key language regions of the brain

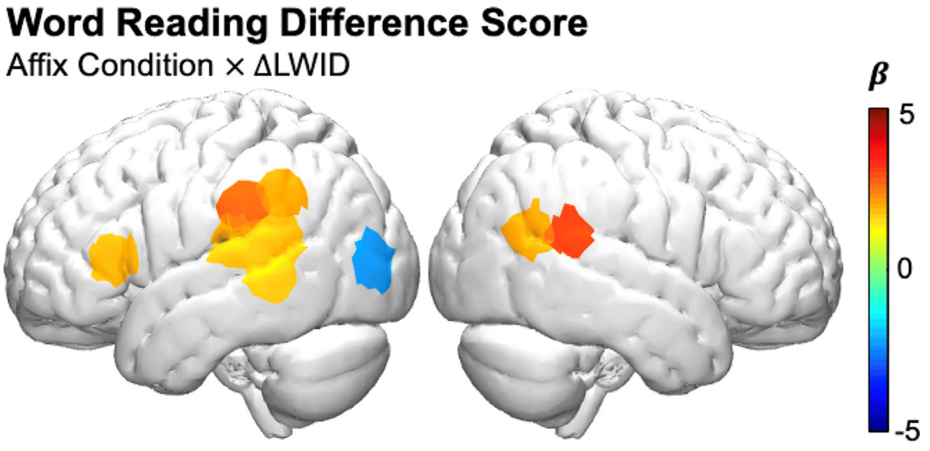

Fig. 3. Brain–behavior interaction between affix processing and reading gains over time. LWID, Letter–Word Identification.

Table 4
Significant brain–behavior interactions with word reading difference score.

Channel		Regions	β	t	p	q	Power
Base Morphemes × Word Reading Gains							
L	2.5	PostCG, STG, PreCG	−2.11	−3.25	.001	.032	.78
L	6.9	MOG, ITG, FG, MTG	−1.86	−3.55	<.001	.016	.86
Affixes × Word Reading Gains							
L	1.1	Ventral IFG, MFG	1.95	3.01	.003	.022	.70
L	2.5	PostCG, STG, PreCG	1.95	3.13	.002	.018	.74
L	2.6	PreCG, PostCG	2.84	4.67	<.001	<.001	.99
L	3.5	STG, PostCG, IPL, TTG	1.95	3.09	.002	.018	.73
L	3.6	PreCG, PostCG, IPL	2.23	3.53	<.001	.008	.85
L	5.5	MTG, STG	1.80	2.83	.005	.033	.63
L	6.9	MOG, ITG, FG, MTG	−2.28	−3.41	.001	.009	.82
R	3.5	STG, PostCG, IPL, TTG	3.04	4.69	<.001	<.001	.99
R	3.7	STG, SMG, IPL, PostCG	2.08	3.49	.001	.008	.84

Note. Channels are notated as [source].[detector] pairings. Regions are reported in the order of greatest probability for each channel. q, Benjamini–Hochberg corrected p values; Power, Type II power calculation at $\alpha = .05$; L = Left hemisphere; R = Right hemisphere; PostCG, postcentral gyrus; STG, superior temporal gyrus; PreCG, precentral gyrus; MOG, middle occipital gyrus; ITG, inferior temporal gyrus; FG, fusiform gyrus; MTG, middle temporal gyrus; IFG, inferior frontal gyrus; MFG, middle frontal gyrus; IPL, inferior parietal lobule; TTG, transverse temporal gyrus; SMG, supramarginal gyrus.

during this morphology task were associated with future reading outcomes 1.5 years later. These findings illuminate mechanisms of spoken language processing that support learning to read and inform theoretical perspectives on the role of morphological awareness in skilled reading.

Spoken language mechanisms predict reading outcomes

Spoken language proficiency lays the foundation for learning to read. Advanced literacy gains are commonly associated with morphological skills that support fluent recognition of words' meaningful morpho-syllables. Nevertheless, prior works on the concurrent relation between spoken and orthographic literacy skills in English typically find a relatively limited extent to which lexical morphology skills contribute to word reading, especially compared with other predictors (e.g., 4.6% for morphology relative to 21% for phonology in Marks et al., 2022; see also McBride-Chang et al., 2005). Importantly, the extent to which morphological competence contributes to broader word reading relative to polymorphemic reading over time appears to be particularly difficult to capture with behavioral measures alone (Levesque & Deacon, 2022). Therefore, we aimed to fill the knowledge gap on the longitudinal relation between lexical morphology and word reading skills through a neurocognitive lens, using both broad and polymorphemic word reading measures.

Our findings reveal robust brain–behavior associations between auditory morphology task activation at Time 1 and reading outcomes at Time 2. This longitudinal evidence connects neurocognitive mechanisms for morphology to reading development over time. We extend prior findings that spoken word processes in temporal brain regions are associated with future reading outcomes, aligning our results for lexical morphology with those previously obtained with whole word processing (Jasińska et al., 2021) and phonological awareness tasks (Wang et al., 2020). We examine these patterns of brain–behavior associations for both the broad and polymorphemic word reading tasks in turn.

The role of the STG

Across all statistical models, we observed a consistent longitudinal brain–behavior association in the bilateral STG. Greater STG activation at Time 1 was associated with better broad word reading skill and polymorphemic word reading at Time 2, as well as steeper gains in word reading over time. In literacy research, the STG is typically associated with dorsal phonological pathways that help to support phonological segmentation and sound-to-letter mapping skills (Jobard et al., 2003). Meaning-based processes have more generally been linked to ventral pathways and brain regions such as the middle temporal regions (Binder et al., 2009; Hickok, 2022; Hickok & Poeppel, 2004). However, there is evidence that STG functionality is not limited to phonological word segmentation but also is implicated in word segmentation that supports both lexical (Ip et al., 2019) and syntactic (Baron et al., 2023) morphological processes. For instance, in Chinese, a language where the orthography represents morphemes, the left STG is more active for morphological awareness tasks than for phonological awareness tasks across both auditory and visual task modalities (Ip et al., 2019). In English, better morphological awareness is associated with greater activation in the left STG during an auditory morphology task (Arredondo et al., 2015). Our current findings extend this work to present evidence that morphophonological segmentation during auditory word processing is associated with future word reading outcomes.

Notably, in the current study, we partialed out the main effects of Time 1 phonological awareness on Time 2 word reading, lending additional specificity to our findings. Children with better phonological awareness skills demonstrate greater engagement of bilateral posterior STG. Nevertheless, the associations between neurocognitive morphological processes and word reading outcomes are robust and separable from the effects of phonology alone. Put another way, individual differences in brain activations for morphological awareness predict future reading outcomes above and beyond the contributions of word reading, phonological awareness, and vocabulary at Time 1.

Stronger associations with affix processing

One noteworthy discovery is that brain activations during affix processing (e.g., *friend-LY*) were more extensively associated with reading outcomes than activations during base processing (e.g., *girl-FRIEND, FRIEND-ship*). Results for the base condition were relatively limited to bilateral temporal regions. Results for the affix condition replicate this association in bilateral temporal regions but also demonstrate positive associations across broader swaths of the reading network. This difference is even more pronounced when examining changes in word reading skill over time. No region of the brain was significantly associated with word reading gains during the base morpheme condition. In contrast, steeper growth over time was associated with greater engagement of the left IFG and bilateral temporoparietal regions, including the left SMG, STG, and MTG, during the affix condition.

This finding extends previous work demonstrating a stronger association between affix processing and concurrent reading comprehension skill than root or base processing (Marks et al., 2022). This is logical because derivation is incredibly productive in English and thus is a common form of lexical variation. In contrast to word bases, which are more semantically concrete but generally have more limited applications, sensitivity to derivational affixes provides a currency that can be applied broadly across many novel words. For instance, knowledge of a root or base morpheme may provide insight into a smaller family of morphologically or etymologically related words (e.g., *civilian, civilization, uncivilized*). In contrast, knowledge of affixes informs children's understanding of both semantics and syntax across a wider range of words (e.g., insight into not only *civic* but also *toxic, mythic, algebraic, harmonic,* etc.). Thus, our findings reflect alignment between neurocognitive mechanisms for language and the underlying characteristics of English.

Another possible explanation for this finding is that children had relatively higher mastery of bases compared with affixes (Marks et al., 2022). Thus, greater activation for affixes than bases, and stronger associations between affixes and reading outcomes, may be driven by several factors: the greater analytic complexity of parsing bound affixes in words, the potential of affix awareness to support word reading more extensively, and children's lower mastery of affixes, resulting in greater room for growth associated with reading development.

Behavioral literature has also demonstrated substantial growth in derivational morphological awareness across the elementary school years related to children's advances in literacy skill (Carlisle & Fleming, 2003). Here, we demonstrated that underlying brain mechanisms for affix processing are more strongly linked to developmental trajectories for reading. Notably, prior work has typically examined derivational morphological awareness in the context of reading comprehension (Deacon et al., 2014, 2017; Kieffer & Lesaux, 2012; Levesque et al., 2017; Marks et al., 2022; Tong et al., 2011). The current study provides new insight into the role of affix processing and its relation to single word reading skills rather than comprehension.

Morphological awareness and theories of reading development

This study found that brain activations during an auditory morphological awareness task predict reading outcomes 1.5 years later. Specifically, greater engagement of bilateral superior temporal regions are associated with steeper reading gains and stronger word reading skills when measured with a standardized broad word reading assessment and with an experimental measure of polymorphemic word reading. This finding informs an ongoing open question in the literacy field about the role of morphological awareness in learning to read both simple and complex words.

Literacy theories situate morphological processes as integral for single-word reading as well as for reading and understanding connected text (Perfetti & Stafura, 2014). Participants in the current study ranged from kindergarten to sixth grade at Time 1. During 1.5 years of reading development, children across this age range gained automaticity in recognizing morphophonemic units to facilitate rapid word recognition. Although beginning English readers rely more heavily on phonological information and sound-to-letter mapping, morphological and semantic information becomes increasingly important as readers gain proficiency (Castles et al., 2018; Ehri, 2005; Nagy et al., 2006).

However, it is less clear if morphological awareness contributes to word reading for *all* words or only for complex polymorphemic words. The *morphological pathways framework* (Levesque et al., 2020) suggests that morphological awareness should specifically facilitate reading polymorphemic words, also referred to as *morphological decoding.* Yet most research to date has examined the statistical contribution of morphological awareness to broader reading skill using standardized measures, which typically ask children to read both morphologically simple words (e.g., *pioneer*) and complex words (e.g., *dangerous*). Thus, there is a conceptual mismatch between theories of morphology in word reading and the majority of available evidence to support those theories.

Many studies have revealed associations between morphological awareness and broad single word reading skill as measured by standardized assessments. For instance, morphological awareness is associated with concurrent word reading in kindergarten through third grade (Marks et al., 2022)). Longitudinal behavioral research has also demonstrated associations between morphological awareness and later reading skill (Deacon et al., 2013, 2014; Kruk & Bergman, 2013; Metsala et al., 2021). However, these studies have generally not included a measure that specifically taps polymorphemic word reading. When monomorphemic and polymorphemic word reading abilities are measured separately, findings typically support a stronger association between morphological awareness and morphological decoding than broader word reading skill. For instance, a study of third and fourth graders found no direct effect of morphological awareness on broad word reading but found that morphological decoding mediated the association (Levesque et al., 2017). Longitudinally, morphological awareness significantly predicted growth in morphological decoding from third grade to fourth grade but found no unique contribution of morphological awareness to broader word reading skill (Levesque

& Deacon, 2022). Thus, Levesque and Deacon (2022) pointed to a discrepancy between theoretical perspectives and extant evidence.

The current study may help to partially explain these behavioral findings and inform this theoretical conundrum more broadly. Our results revealed brain–behavior associations during a morphological awareness task with broader word reading skill, as measured by a standardized assessment, as well as with an experimental measure of polymorphemic word reading. When using this more proximal experimental measure, however, we saw a larger swath of brain regions that are associated with future reading outcomes. Broad word reading outcomes are associated with activation in three left hemisphere and four right hemisphere regions. Polymorphemic word reading, in contrast, is associated with greater activation in five left hemisphere channels, including the IFG and parietal regions, and eight right hemisphere channels, including four channels clustered around the right inferior frontal and precentral gyri. In other words, the significant associations in the bilateral temporal cortex with future reading outcomes are replicated and extended when using an experimental task that specifically taps morphological decoding and visual morphological awareness.

The broader brain–behavior associations for polymorphemic word reading may also be related to the more explicit morphological judgments required of both the imaging task and the behavioral outcome measure. Interestingly, however, accuracy on the polymorphemic word reading task was more closely correlated with single word reading and reading comprehension skills at Time 1 and Time 2 than with accuracy on the fNIRS morphological awareness task or the behavioral morphological awareness measure (Table 2). Greater associations across the language network between morphological awareness activations and polymorphemic word reading are likely related to the increased demands on morphological processes associated with the outcome measure. These increased demands are both implicit in reading complex words and explicit because of the metalinguistic judgment required by the visual morphology task.

These findings speak to the importance of measurement specificity and provide neurocognitive evidence of stronger associations between auditory morphological awareness and polymorphemic word reading as compared with word reading more generally. Furthermore, the regions that reveal these longitudinal brain–behavior associations extend beyond the ventral regions typically associated with meaning processing. Future polymorphemic word reading skill is associated not only with greater activation in the left MTG and left IPL—two hubs of semantic processing (Binder et al., 2009)—but also with bilateral frontal and superior temporal regions. Thus, we see that greater engagement across the entire perisylvian language network during morphological awareness is associated with emerging literacy skill. This engagement across the language network may reflect the integrative nature of morphological processing, or the role of morphemes as a "binding unit" (Kirby & Bowers, 2017) that links sound, meaning, and print.

Classic models of word reading include morphology implicitly, but do not explicitly specify the mechanisms by which morphology may influence word recognition. The "triangle model" of word reading (Seidenberg & McClelland, 1989) describes links among phonological, semantic, and orthographic representations of words within a connectionist network. This network also includes hidden units that allow for more complex mapping of orthography to phonology. For instance, direct connections between orthography and phonology would result in equivalent pronunciation of the vowel sound in *heal* and *health;* hidden units allow for more nuanced associations between word constituents. Other theoretical perspectives (Kirby & Bowers, 2017; Levesque et al., 2020; Perfetti & Stafura, 2014) are more explicit about the role of morphology in word- and sentence-level reading skills. For instance, Kirby and Bowers (2017) specified that morphology is a "binding agent" that strengthens connections among word orthography, phonology, and semantics, supporting increased automaticity in word reading. In the case of *heal* and *health,* skilled readers may use their past learning experiences, information from context, and their implicit morphological awareness to understand the semantic relations between these two words as well as the divergence in pronunciation. Our findings expand this perspective by revealing significant brain–behavior associations between morphological processes and learning to read. Specifically, our findings inform theories of literacy development by revealing an association between neurocognitive mechanisms for morphological awareness and literacy growth over time, particularly for reading polymorphemic words.

Limitations

Our study has a few important limitations. The current study spans a wide age range that may mask age- or proficiency-related differences in reading processes such as increased reliance on morphology over time. We note the high SES of our sample, which may limit generalizability. We also note that we collected data in person at Time 1 and online at Time 2. This was because Time 1 data collection took place before the global COVID-19 pandemic, whereas Time 2 took place in the midst of the pandemic during the first full year of remote schooling. Despite schooling disruptions, the participants in the current study, on average, grew in their reading skills as expected according to traditional norms. This is a departure from other studies revealing slowed reading growth, particularly among historically marginalized students (Kuhfeld et al., 2023). Nevertheless, COVID-19 likely influenced our sample's psychosocial and academic development during this period in ways that we are unable to account for.

Our neurocognitive results suggest that engagement across the language network is associated with future reading outcomes. This may be in part a result of the methodological approach. Because hemodynamic imaging methods capture data along a slower time course than electrophysiological methods, findings may reflect more integrative processes by nature rather than system-specific processes involved in early word decomposition (Gwilliams, 2020). In addition, our morphological awareness task requires children to hold multiple words in working memory and make an explicit judgment about meaning. Future work with masked priming paradigms may provide valuable insight into implicit and rapid morphological processes that complement the current findings.

Finally, although our study included measures of broad word reading ability and morphological decoding, we did not have a measure that solely tapped monomorphemic word reading. To fully tease apart the role of morphology in simple versus complex word reading, future research may consider matched measures that ask children to read polysyllabic monomorphemic words (e.g., *elephant, umbrella*) as compared with polymorphemic words (e.g., *entirely, unworkable*). A particular challenge will be to match words on frequency and concreteness given that monomorphemic words tend to be more concrete (Steacy et al., 2022; Strik Lievers et al., 2021). Reconciling the complexities of English word reading will be important in future work.

Conclusion

Learning to read builds on spoken language skill, yet little is known about how specific spoken language processes set the stage for future reading success. The current study addressed this gap by examining the neurocognitive mechanisms underlying morphological processing. We found that brain activations during an auditory morphology task are associated with reading outcomes 1.5 years later, even when controlling for initial reading skill. Greater engagement across the language network when processing spoken morphemes, particularly in the bilateral STG, is associated with better word reading and steeper reading growth over time. These findings deepen our understanding of the specific components of language processing that are associated with reading development beyond phonological awareness and further the ongoing theoretical conversation about the role of morphological awareness in reading simple and complex words.

Data availability

Data are available at https://doi.org/10.1016/j.dib.2022.108048

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2023.105802.

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