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Lexical Morphology as a Source of Risk and Resilience for Learning to Read With Dyslexia: An fNIRS Investigation

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ABSTRACT

Purpose: We examined the neurocognitive bases of lexical morphology in children of varied reading abilities to understand the role of meaning-based skills in learning to read with dyslexia.
Method: Children completed auditory morphological and phonological awareness tasks during functional near-infrared spectroscopy neuroimaging. We first examined the relation between lexical morphology and phonological processes in typically developing readers (Study 1, $N = 66$, $M_{age} = 8.39$), followed by a more focal inquiry into lexical morphology processes in dyslexia (Study 2, $N = 50$, $M_{age} = 8.62$).
Results: Typical readers exhibited stronger engagement of language neurocircuitry during the morphology task relative to the phonology task, suggesting that morphological analyses involve synthesizing multiple components of sublexical processing. This effect was stronger for more analytically complex derivational affixes (*like* + *ly*) than more semantically transparent free base morphemes (*snow* + *man*). In contrast, children with dyslexia exhibited stronger activation during the free base condition relative to derivational affix condition. Taken together, the findings suggest that although children with dyslexia may struggle with derivational morphology, they may also use free base morphemes' semantic information to boost word recognition.
Conclusion: This study informs literacy theories by identifying an interaction between reading ability, word structure, and how the developing brain learns to recognize words in speech and print.
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Words are universally composed of one or more units of meaning, called *lexical morphemes*. Children with dyslexia, a neurodevelopmental disorder that affects 6%–20% of the population (Wagner et al., 2020), typically struggle with language sounds (phonology). However, there is conflicting behavioral evidence on whether morphological processes are also impaired in the disorder. Some studies have found dyslexia-related morphological awareness (MA) deficits (Berthiaume & Daigle, 2014; Casalis et al., 2004; Melloni & Vender, 2022), whereas others have argued that individuals with dyslexia may use MA as a source of strength in learning to read (Cavalli, Duncan, et al., 2017; Law & Ghesquière, 2021). Neuroimaging approaches to the study of literacy development complement standard behavioral research by shedding additional light on mechanisms that underlie word recognition and how it may differ in dyslexia (Hoeft et al., 2007). Accordingly, the present study investigates the neurocognitive bases of MA in children of varied reading abilities. We ask two main questions. First, how does MA compare to phonological awareness (PA) at the single-word processing level? Second, are there differences in the brain bases of MA between children with dyslexia and younger children of the same reading level?

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Morphological Awareness

MA is our sensitivity to words' smallest units of meaning and structure. Lexical morphemes, the focus of the present work, include free base units (e.g., "snow" and "man" in *snow* + *man*) as well as derivational affixes (e.g., "un" and "ly" in *un* + like + *ly*). Free base morphemes are stand-alone units that are more semantically transparent and can be used to form compound words or be modified by affixes (Nagy et al., 2014). In contrast, derivational affixes are relatively abstract and do not stand alone. Children's proficiency and awareness of free base morphemes develop earlier and more quickly than their proficiency and awareness of derivational affixes (Clark, 1993; Kuo & Anderson, 2006). Such distinction in semantic transparency and analytical complexity allows us to probe efficiencies and shortcomings of morphological processing in the context of complex polymorphemic word recognition, a critical skill for advanced literacy.

Brain-Behavior Perspectives on Lexical Morphology

Literacy theories often consider MA a multidimensional skill that contributes to single-word recognition and text comprehension at multiple levels of processing (Levesque & Deacon, 2022). At the single-word level, MA is considered a "binding agent" that connects a word's phonological, semantic, and orthographic representations (Kirby & Bowers, 2017; Perfetti & Hart, 2002). Neuroimaging studies generally support this viewpoint. Morphology tasks typically engage neurocircuits associated with phonology (including the dorsal aspect of the left inferior frontal gyrus (IFG) and superior temporal gyrus (STG), as well as those associated with semantics (including the ventral aspect of the left IFG and middle temporal gyrus [MTG]; Arredondo et al., 2015; Ip et al., 2019; Marks et al., 2021; Sun, Marks, et al., 2022). Notably, our understanding of the neurobiological bases of morphology in relation to child literacy remains sparse, especially in relation to dyslexia (see the Brain Bases of Morphology in Children with and without Dyslexia section below).

Gwilliams' (2020) neurocognitive view of morphology posits that recognizing free bases and derivational affixes engages different processes. According to this theory, recognition of polymorphemic words is a multistage process. These stages include phonological segmentation (engaging phonological neurocircuitry, e.g., STG), matching segments to their meanings (engaging semantic neurocircuitry, e.g., MTG), and synthesizing those segments into an analytically complex whole (engaging complex language analytics, e.g., IFG). The first two stages may suffice to efficiently recognize free base words, whereas all three stages may be necessary to recognize derived words. Phonology and complex language analyses are often impaired in dyslexia (see Melby-Lervåg et al., 2012, for a review). This theoretical perspective thus yields the following prediction: Should semantic processing be less affected than phonological processing in children with dyslexia, they may be more efficient (or less impaired) at processing words that consist only of free bases than words that require the analysis of both a base and a derived affix.

Morphological Awareness in Dyslexia

Children with dyslexia typically underperform on MA tasks in comparison to typical readers of the same age (Berthiaume & Daigle, 2014; Casalis et al., 2004; Melloni & Vender, 2022; Tsesmeli & Seymour, 2006). At the same time, children with dyslexia tend to perform similarly to younger children of their reading level (see Deacon et al., 2019, for a review). Some researchers have argued that lower morphological performance in children with dyslexia is a downstream consequence of poor PA and reduced reading experience. For example, Casalis et al. (2004) found that children with dyslexia performed lower than reading-matched controls on MA tasks that relied more heavily on phonological skills (e.g., segmenting multimorphemic words), but performance was comparable on morphological sentence completion tasks that relied less on phonology (e.g., [politeness] . . . this boy is [polite]). In addition, Law et al. (2017) found that preschool children with a familial risk of dyslexia performed lower on an auditory task of derivational and inflectional morphology than age-matched peers. However, these group differences disappeared after controlling for PA. Taken together, these findings suggest that lower MA performance in children with dyslexia may be a consequence and not a distinct impairment of the disorder.

Notably, some studies have suggested that morphological competence may be a source of strength for learning to read with dyslexia. For example, Cavalli, Duncan, et al. (2017) found that French-speaking college students with dyslexia with a larger gap between their MA and PA proficiency (with substantially better MA) were better readers. Notably, the association between this discrepancy and reading performance was not significant in typical readers. A study by Law et al. (2015) with English-speaking college students made a similar observation. Better readers with dyslexia had higher morphological but similar PA abilities than below-average readers with dyslexia. These two studies with college students interpreted their findings as suggesting a compensatory role of morphology in literacy success with dyslexia. Finally, a landmark study by Elbro and Arnbak (1996) found that Dutch-speaking children with dyslexia read polymorphemic words faster than monomorphemic words with the same number of syllables, whereas typically developing children showed similar performance across word types. The researchers interpreted their findings as suggesting that lexical morphemes may play a unique role in fostering visual word recognition in dyslexia. In our study, we extend this prior work using a neurocognitive approach to further probe morphological processes in relation to phonological processes in children with dyslexia.

Brain Bases of Morphology in Typical Reading and Dyslexia

Neuroimaging is a complementary tool that allows us to examine the neurocognitive mechanisms that underlie children's MA performance. MA tasks have been shown to activate both sound and meaning networks as proposed by Gwilliams' (2020) model (Arredondo et al., 2015; Marks et al., 2021). This activation during auditory morphological processing has been linked to reading at the single word and passage level. In a longitudinal study using functional Near Infrared Spectroscopy (fNIRS), Marks et al. (2024) found an association between superior temporal engagement at Time 1 and polymorphemic word reading skill 1.5 years later. Another fNIRS study of skilled and impaired readers by Marks et al. (2021) found that children with stronger reading comprehension skill exhibited stronger activation in left inferior frontal, middle temporal, and inferior parietal regions associated with integrating word sound and meaning. In contrast, poor reading skill in dyslexia was associated with less robust engagement of key regions involved in integrating word sounds, meaning, and structure. This neurocognitive difference was heightened during task conditions that required children to attend to affixation rather than free base morphemes. Although this study included both typical readers and children with dyslexia, the continuous analytic approach leaves open questions about possible qualitative differences between typical readers and children with dyslexia in the processes underlying MA and their association with reading skill.

Studies of the neurocognitive basis of MA in dyslexia are sparse. An fMRI study revealed differences in derivational morphological processing between age-matched elementary school children with and without dyslexia (Aylward et al., 2003). Children were asked to read English word pairs and determine whether they shared a morpheme (e.g., builder-build vs. corner-corn). Children with dyslexia exhibited lower activation in left MFG, right parietal, and bilateral fusiform areas, suggesting potential deficits in analytical and orthographic processing of morphology.

Studies of college students with dyslexia have consistently suggested that morphology may be a source of strength that is associated with remediation (Bitan et al., 2020; Cavalli, Colé, et al., 2017; Cavalli, Duncan, et al., 2017; Law et al., 2015). At the neurocognitive level, students with dyslexia showed a stronger and earlier-emerging morphological priming effect in left frontal regions than age-matched controls (Cavalli, Colé, et al., 2017). Results of an fMRI study with Hebrew-speaking college students offer a similar finding (Bitan et al., 2020). In this study, only college students with dyslexia (but not neurotypical readers) showed stronger activation in left occipitotemporal regions when reading words with added phonological cues, suggesting a stronger reliance on morpho-orthographic cues in dyslexia.

Notably, across these prior works, experimental tasks generally tapped into participants' ability to recognize and analyze the free base morphemes within a derived word (e.g., as in *corner-corn* vs. *builder-build*). It is therefore unclear whether the observed deficits (Aylward et al., 2003) or benefits (Cavalli, Colé, et al., 2017) of morphological competence in dyslexia stem from children's processing of free base units of meaning, rules of affixation, or some combination of the two. It is critical to the advancement of both literacy theory and practice that we gain a more complete understanding of children's developing component subprocesses of lexical morphology and how they are affected in dyslexia.

The Current Study

This study aimed to shed light on component processes of lexical morphology in young readers with and without dyslexia. Intrigued by the idea that some elements of morphological processing may be a source of strength for children with dyslexia, we aimed to isolate meaning- and structure-based processes of lexical MA. To do so, we designed an auditory morphology task with free base and derivational affix conditions. Children heard three words and determined which two shared a morpheme (free base: classroom-bedroom-mushroom; affix: dancer-waiter-corner). This task also included a phonology condition, in which participants determined which two words shared an initial phoneme (*mother* - *major* - *father*) and whole-word control condition (*laundry* - *laundry* - *bookshelf*). We chose the auditory modality in combination with child-friendly, silent fNIRS neuroimaging because neurocognitive mechanisms for spoken language processing predict reading development (Marks et al., 2019), and to avoid confounding factors such as group differences in visual word recognition.

To uncover underlying mechanisms of lexical morphology processing in dyslexia, we first examined the relation between lexical morphology and phonological neurocognitive processes in typically developing readers (Study 1), followed by a more focal inquiry into lexical morphology processes in dyslexia (Study 2). In Study 1, we aimed to identify the unique and overlapping neurocognitive mechanisms for processing phonemes (phonology condition) as compared to two types of morphemes: derivational affix and free base. We predicted that the morphology task would elicit stronger engagement of both phonological and semantic pathways than the phonology task as morphology is thought to bind words' phonological and semantic representations (Kirby & Bowers, 2017). After distinguishing morphological and phonological processing in Study 1, in Study 2, we sought to examine the effects of dyslexia on lexical morphology processes by comparing children with dyslexia to younger reading-matched controls. Guided by Gwilliams' (2020) neurocognitive framework, we hypothesized that the predicted differences between free base and affix processing in typically developing readers may be qualitatively different in children with dyslexia. Should meaning be the primary source of strength in word recognition with dyslexia, children with dyslexia should show more efficient processing (as reflected in high task performance and engagement of semantic neurocircuitry) during the free base than the affix condition. In sum, the present study offers a thorough inquiry into the neurobiology of lexical morphology component processes in children of varied reading abilities.

Materials and Method

Participants

Ninety-one English-speaking monolingual children participated: 66 neurotypical and 25 with dyslexia (M_{age} = 8.77, *SD* = 1.55; 43 boys, 48 girls; see Table 1). Children were included in the study if their vocabulary and working memory scores fell within the typical range and their accuracy on the experimental fNIRS tasks was above chance. Our sample was 77% White, 19% multiracial/multi-ethnic, 2% Black, 1% Latino, and 1% Asian. Mean parental educational attainment was 8.90 on an 11-point scale, corresponding to some postbaccalaureate schooling. The median family income range was $100,000–$149,999. The study was approved by the University of Michigan Institutional Review Board. Informed consent and assent were obtained for each guardian and child, respectively.

Study 1 included 66 neurotypical children who scored 85 or above on all standardized measures of language and literacy. Study 2 included 25 children with dyslexia and 25 controls (a subset of the 66 children in Study 1 children) matched on word reading and passage comprehension raw scores (see Table 1). Participants were characterized as having dyslexia if they met at least one of the following criteria: (a) standard scores of 85 or below on two or more standardized literacy assessments listed below; (b) caregiver report of a reading impairment, and a standard score of 90 or below on at least one standardized literacy assessment. Sixteen participants (64%) met both criteria, six participants (24%) met the testing criteria only, and three participants (12%) had a diagnosed reading impairment but performed in the typical range on most standardized reading assessments on the day of testing. These three participants' parents reported that they received Special Education services in reading in school. This remediation may explain their typical performance during testing.

Language and Literacy Measures

Receptive vocabulary and working memory were measured using the Peabody Picture Vocabulary Test–Fifth Edition (Dunn, 2018) and Backward Digit Span from the Weschler Intelligence Scale for Children–Fifth Edition (Weschler, 2014), respectively. Literacy and dyslexia inclusion criteria were assessed using the Comprehensive Test of Phonological Processing Elision subtest (Wagner et al., 2013), Letter-Word Identification (word reading), Word Attack (decoding), Passage Comprehension, and Sentence Reading Fluency Woodcock–Johnson IV subtests (Schrank et al., 2014), as well as a word-fluency measure (Test of Word Reading Efficiency–Second Edition; Torgesen et al., 2012).

MA was measured using the Early Lexical Morphology Measure (ELMM; Marks et al., 2022). Children listened to a word and were instructed to use part of that word to complete a sentence (e.g., *Friendly. She is my best* ___. [friend]). ELMM has been validated with 350 children of varied reading ability, has a reliability of α = .93, and predicts unique variance in word reading after controlling for vocabulary and PA (Marks et al., 2022; also detailed in Sun, Zhang, et al., 2022).

Neuroimaging Tasks and Stimuli

Participants completed morphological and phonological auditory word matching tasks during fNIRS neuroimaging. In each trial, participants heard three words and used a button press to select which of the last two words matched the first (target) word. Each task included 48 trials divided into four four-trial blocks. Each block lasted 30 s, separated by 6 s of rest, totaling approximately 7.2 min per task. The order of blocks and correct responses was randomized (for a complete description and training procedure, see Sun, Zhang, et al., 2022).

MA imaging task included two conditions: Free Base (e.g., *teammate – animate – classmate)* and Derivation (e.g., *reset – reading – replay*). Each word triplet contained a target word, morphological match, and phonological distractor.

PA imaging task required participants to match two words on their starting sound while ignoring a semantic distractor. The task included two conditions. The less complex onset-rime condition did not include glides or diphthongs,

Table 1. Descriptive information and behavioral results for Studies 1 and 2.

Variable		Study 1: Typically developing	Study 2: Reading-matched control	Study 2: Dyslexia	*p* values
N		66	25	25	
Gender (male)		42%	64%	60%	
		M (*SD*)	*M* (*SD*)	*M* (*SD*)	Dyslexia vs. Reading-matched control
Age		8.39 (1.51)	7.46 (1.33)	9.77 (1.19)	< .001
Parental education		9.27 (1.56)	9.42 (1.43)	7.84 (1.81)	.001
MA (ELMM)		30.09 (8.34)	23.76 (9.01)	27.40 (6.30)	.100
PA	Standard	10.89 (2.06)	10.68 (2.23)	6.68 (2.38)	< .001
	Raw	24.62 (5.81)	21.24 (5.55)	18.84 (5.60)	.134
Vocabulary	Standard	119.94 (16.31)	115.50 (10.57)	104.52 (14.37)	.004
	Raw	171.23 (22.65)	157.71 (19.06)	168.36 (15.42)	.037
Word reading	Standard	111.83 (12.76)	104.32 (11.11)	78.08 (15.98)	< .001
	Raw	53.15 (13.07)	42.44 (10.45)	40.79 (12.69)	.623
Decoding	Standard	112.05 (12.36)	106.54 (12.25)	87.09 (13.81)	< .001
	Raw	21.22 (5.68)	16.75 (4.25)	16.05 (4.71)	.598
Passage comprehension	Standard	106.73 (9.88)	104.48 (9.94)	75.14 (15.86)	< .001
	Raw	30.15 (7.63)	24.76 (6.83)	23.05 (7.26)	.418
Sentence reading fluency	Standard	109.55 (13.05)	104.91 (10.50)	79.20 (12.78)	< .001
	Raw	44.24 (19.21)	31.55 (15.87)	27.50 (14.13)	.387
Working memory		7.56 (1.88)	7.40 (1.85)	7.24 (1.54)	.741
fNIRS MA task accuracy (%)					
Free base		85.61 (14.91)	82.03 (10.80)	79.50 (14.27)	.486
Affix		74.34 (18.83)	68.23 (19.58)	73.25 (17.54	.350
Whole word		94.03 (17.31)	95.74 (5.59)	95.75 (6.43)	.995
fNIRS MA task reaction time (ms)					
Free base		1,748 (300)	1,780 (294)	1,807 (310)	.756
Affix		1,888 (267)	1,929 (233)	1,891 (262)	.590
Whole word		1,438 (240)	1,486 (211)	1,405 (218)	.196
fNIRS PA task accuracy					
Onset-rime		86.99 (13.11)	79.75 (17.24)	81.50 (13.32)	.690
Onset-phoneme		70.96 (15.48)	68.50 (12.43)	62.50 (20.49)	.218
Whole word		96.44 (5.30)	91.30 (10.45)	91.48 (8.31)	.951
fNIRS PA task reaction time					
Onset-rime		1,423 (317)	1,457 (364)	1,480 (304)	.807
Onset-phoneme		1,530 (328)	1,575 (280)	1,572 (339)	.974
Whole word		1,307 (254)	1,273 (266)	1,330 (237)	.431

Note. MA = morphological awareness; ELMM = early lexical morphology measure; PA = phonological awareness; fNIRS = functional Near Infrared Spectroscopy.

and/or the initial sound of the distractors was phonetically distant from the target words (e.g., *Sunday – Monday – subway*), whereas the more complex onset-phoneme condition contained glides or diphthongs and/or the initial sounds of the distractors were phonetically similar to the target words (e.g., *teeth – truth – mouth*).

Whole-word control condition, in which participants matched two identical words (e.g., *laundry – bookshelf – laundry*), was designed to isolate morphological and phonological processing by controlling for more basic word recognition processes.

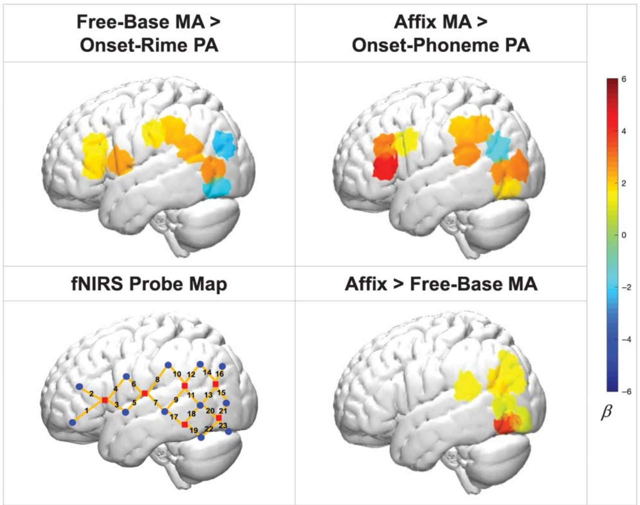
Experimental stimuli were matched for word length (number of phonemes, syllables, letters), age of acquisition (Goh et al., 2020), and frequency (Corpus of Contemporary American English; Davies, 2020). The fNIRS task validation with 343 children suggests high reliability for both morphology (α = .99) and phonology (α = .98; for details, measures, and de-identified data see Sun, Zhang, et al., 2022).

fNIRS Data Acquisition and Processing

fNIRS data were collected using a TechEN-CW6 system with 690 and 830 nm wavelengths. We used the international 10–10 system to construct silicone headbands with sources and detectors corresponding to inferior frontal and temporoparietal language regions, which were identified by prior literature. Figure 1 depicts the probeset of 23 channels per hemisphere. As described by Hu et al. (2020), MRI imaging and photogrammetry optode registration were used to localize these channels in Montréal Neurological Institute (MNI) stereotactic space. Trained experimenters measured each participant's head circumference and identified nasion, inion, Fpz, and left and right pre-auricular points. Cardiac signal in frontal channels was monitored to ensure correct optode placement. Supplemental Material S7 details the estimated regions covered by each channel and midpoint MNI coordinates.

Subject- and group-level analyses were conducted using the NIRS Brain AnalyzIR Toolbox (Santosa et al., 2018), a MATLAB (MathWorks)–based software. Individual-level analyses began with preprocessing procedures (Sun, Marks, et al., 2022). The modified Beer–Lambert law was used to convert optical density data to hemoglobin concentration data, which was then analyzed using the general linear model (GLM; Friston, 2009). To account for noise at the individual-level, we used the AR-IRLS method (prewriting and auto-regressive model; Barker et al., 2013, and Caballero-Gaudes & Reynolds, 2017). Temporal and dispersion derivatives were added to the canonical hemodynamic response function and the discrete cosine transform matrix to account for signal drift over time. The single subject GLM yielded estimated individual-level regression coefficients for oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) signals collected from each channel.

Figure 1. Study 1 left hemisphere brain activations. Direct comparisons of free base and affix conditions to phonology and affix to free base (task > rest; all false discovery rate adjusted $q < .05$). Light sources and detectors in the functional Near Infrared Spectroscopy (fNIRS) Probe Map are represented by squares and circles, respectively. MA = morphological awareness; PA = phonological awareness.



Free-Base MA > Onset-Rime PA

Affix MA > Onset-Phoneme PA

fNIRS Probe Map

Affix > Free-Base MA

Group-level analyses were then conducted using linear mixed-effects models for each data channel, including subject as a random effect. In Study 1, we modeled the interaction between task (morphology or phonology) and condition (morphology: free base, affix; phonology: onset-rime, onset-phoneme) to predict individual-level beta values. The model included age, family income, and fNIRS task reaction time (RT) as covariates (analytical formula: beta ~ task × condition + age + income + reactiontime + (1|Subject)). In Study 2, we modeled the interaction between morphological task condition (free base, affix, and whole-word control) and participant group (children with dyslexia and reading-matched controls). The model included the same covariates as in Study 1 (analytical formula: beta ~ group × condition + age + income + reactiontime + (1|Subject)). Estimated group-level channel-based effects were extracted for the contrasts experimental condition(s) > whole-word control. We also examined the interaction between brain activation during the MA task and out-of-scanner MA performance (i.e., ELMM) separately for each group (all typically developing participants, children with dyslexia, and reading-matched controls), using the model: beta ~ −1 + condition × ELMM + age + income + reactiontime + (1|Subject).

We plotted the group-level effects (unstandardized betas) for each contrast on the MNI 152 brain template using previously digitized MNI coordinates (Hu et al., 2020). We present HbO analyses below 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). Neuroimaging findings presented in this article have survived false discovery rate (FDR; Benjamini-Hochberg) correction for multiple comparisons.

Results

Study 1: Morphological Versus Phonological Processing in Typical Development

Behavioral Performance

Participants completed morphological (MA) and phonological (PA) auditory word matching tasks during fNIRS neuroimaging. Children performed similarly on both tasks; MA accuracy *M* (*SD*) = 79.48 (16.87), PA accuracy *M* (*SD*) = 79.98 (14.30), see Table 1; each of which contained two experimental conditions and a whole-word control condition (MA: free base, affix; PA: onset-rime, onset-phoneme).

Accuracy analyses revealed a significant main effect of condition, $F(2, 126) = 140.77$, $p < .001$, and no significant main effect of task, $F(1, 63) = 0.019$, $p = .89$. Children had the highest accuracy for the whole-word control conditions and the lowest accuracy for the affix (MA)/onset-phoneme (PA) conditions (all Bonferroni-corrected ps < .001). There was a significant Task × Condition interaction, $F(2, 126) = 0.02$, $p = .033$, as children performed slightly higher on the onset-rime PA condition, M (SD) = 86.99 (13.11), than the free base MA condition, M (SD) = 85.61 (14.91), yet slightly higher on the affix MA condition, M (SD) = 73.34 (18.83), than the onset-phoneme PA condition, M (SD) = 70.96 (15.48).

RT analyses revealed a significant main effect of task, $F(1, 62) = 119.38$, $p < .001$, and condition, $F(2, 124) = 100.14$, $p < .001$, as well as an interaction, $F(2, 124) = 17.00$, $p < .001$. Post hoc analyses further revealed that participants responded more quickly during the PA, M (SD) = 1,419 (311) ms, than the MA, M (SD) = 169 (328) ms, tasks ($p < .001$). Regarding the conditions, the children had the fastest RT during the whole-word conditions, followed by free base (MA)/onset-rime (PA) conditions, followed by the affix (MA)/onset-phoneme (PA) conditions (all Bonferroni-corrected ps < .001). The interaction stems from slower RT for the affix MA than onset-phoneme PA condition, with no RT differences between whole-word conditions. Neuroimaging analyses thus controlled for RT.

Patterns of Brain Activation

MA versus PA. As shown in Figure 1 (see Supplemental Materials S1 and S4), direct comparisons between the tasks (free base MA > onset-rime PA; affix MA > onset-phoneme PA contrasts) revealed that MA yielded stronger and more wide-spread activation patterns relative to PA. Free base MA condition elicited stronger activation in a total of 11 channels (seven left, four right) overlaying bilateral IFG and temporo-parietal regions whereas onset-rime PA elicited stronger activation in a total of three channels (two left, one right) overlaying left inferior parietal/angular gyrus and bilateral inferior-temporal regions. Affixes elicited stronger activation in a total of 14 channels (nine left, five right) overlaying left IFG, left occipito-temporal, and bilateral temporo-parietal regions. Onset-phoneme PA elicited stronger activation in one channel overlaying left supramarginal/STG regions (see Figure 1 for left hemisphere activations and fNIRS probe map, Supplemental Material S1 for bilateral activations, and Supplemental Material S4 for bilateral *beta* and *t* values).

Free base versus derivational affix. Affixes elicited stronger activation in 11 channels (seven left, four right) overlaying bilateral temporo-parietal, left occipital and right IFG/MFG frontal regions, whereas the free base condition elicited stronger activation in three right hemisphere channels including IFG and occipito-parietal.

Brain-behavior associations. We modeled the interaction between performance on the behavioral morphology measure (ELMM) and brain activation during the morphology conditions (see Figure 3 for left hemisphere activations, Supplemental Material S3 for bilateral activations, and Supplemental Material S6 for bilateral *beta* and *t* values). Children with better morphological competence showed less activation in bilateral STG regions and stronger activation in bilateral occipito-temporal regions.

Study 2: Morphological Processing in Typical Development Versus Dyslexia

Behavioral Performance

Children with dyslexia were matched to a subset of typically developing participants (reading-matched controls) on raw measures of word reading ($M_{\text{difference}} = 1.65$, $p = .623$) and reading comprehension ($M_{\text{difference}} = 1.71$, $p = .418$; see Table 1). The groups also did not significantly differ on raw measures of phonology, morphology, decoding, fluency, and working memory (ps > .1; see Table 1). We examined morphological processes using morphology minus whole-word condition contrasts because the two groups did not differ significantly on the whole-word condition accuracy ($M_{\text{difference}} = 0.01$, $p = .995$).

There were no accuracy or RT differences between children with dyslexia and reading-matched controls during each condition of the MA neuroimaging task. Task performance was similar to Study 1 and similar across groups. Separate analyses of variance for accuracy and RT (2 groups × 3 conditions) revealed a significant main effect of condition, accuracy: $F(2, 96) = 31.83$, $p < .001$; RT: $F(2, 92) = 94.41$, $p < .001$, but no significant main effect of group, accuracy: $F(1, 48) = 1.53$, $p = .22$; RT: $F(1, 46) = 0.25$, $p = .62$. The whole-word condition yielded the highest accuracy and lowest RT, followed by the free base condition, followed by the affix condition, accuracy: ps < .001; RT: ps ≤ .01 (Bonferroni corrected). Finally, the Group × Condition interaction was not significant for accuracy, $F(2, 96) = 1.07$, $p = .35$, or RT, $F(2, 92) = 1.20$, $p = .31$.

Patterns of Brain Activation

Free base. Reading-matched controls exhibited significant activation in five channels (three left, two right) overlaying left IPL and bilateral inferior temporal regions. Children with dyslexia exhibited significant activation in two left hemisphere channels overlaying ventral IFG and MTG.

Derivational affix. Reading-matched controls exhibited significant activation in two left hemisphere channels overlaying dorsal IFG and left MTG. In children with dyslexia, no brain region was significantly more active during the affix condition relative to the whole-word condition.

Derivational affix versus free base. Reading-matched controls exhibited stronger left middle occipital gyrus and weaker left IPL and right ITG activation during affix relative to free base. Children with dyslexia exhibited stronger left MTG/AG and right ventral IFG activation during the affix relative to free base condition. Children with dyslexia exhibited stronger activation during the free base relative to affix condition in 13 channels (five left, eight right) overlaying bilateral temporo-parietal and right frontal/inferior temporal regions (see Figure 2 for left hemisphere activations, Supplemental Material S2 for bilateral activations, and Supplemental Material S5 for bilateral *beta* and *t* values).

Regions of interest. The left MTG and left ventral IFG were chosen as a priori regions of interest because of their involvement in semantic processing (see Figure 2; Hagoort, 2019). Reading-matched controls and children with dyslexia did not significantly differ in their engagement of the left MTG, $t(48) = 1.70$, $p = .10$, or left ventral IFG, $t(48) = 0.05$, $p = .96$, during the free base condition. During the affix condition, children with dyslexia exhibited weaker activation in left MTG, $t(48) = 3.27$, $p < .01$, and left ventral IFG, $t(48) = 2.323$, $p = .025$, relative to reading-matched controls.

Brain-behavior associations. Brain-behavior associations were modeled similarly to Study 1, separately for each group (see Figure 3 for left hemisphere activations, Supplemental Material S3 for bilateral activations, and Supplemental Material S6 for bilateral *beta* and *t* values). Reading-matched controls, similar to the larger typical reader group, showed negative STG and positive occipito-temporal associations between morphological competence and brain activation across the two conditions. Children with dyslexia showed positive brain-behavior associations in left parietal regions, with additional negative association with left MTG and positive association with right parietal for the affix condition.

Discussion

The study aimed to uncover the neurocognitive mechanisms of lexical morphology processing in children with and without dyslexia. Word meaning, in English and other languages, is revealed through lexical morphemes. These morphemes vary in their degree of semantic transparency and structural complexity. Free base morphemes (*snow* + *man*) are more semantically transparent, whereas derivational affixes ("ly" in like + *ly*) are more abstract and analytically complex. Consistent with this distinction, typically developing readers (Study 1) exhibited lower performance and stronger activation of the language network when processing derivational affixes than free base morphemes. Children with dyslexia (Study 2), in contrast, exhibited stronger activation of the language network when processing free base morphemes, especially along the semantic network. These results inform literacy theory by deepening our understanding of the neurocognitive component processes of lexical morphology and suggesting that free base morpheme recognition may be a source of resilience in word recognition in dyslexia.

Study 1: Morphological and Phonological Processes in Typical Readers

The goal of Study 1 was to uncover how children process free base and derivational affix morphemes in relation to each other and to phonological processes. Prior

Figure 2. Study 2 brain activations and regions of interest (left middle temporal gyrus and left ventral inferior frontal gyrus) analyses. Within-group morphological awareness neuroimaging task condition comparisons for children with dyslexia and reading-matched controls. Only positive activation is displayed for all contrasts except Affix > Free Base. False discovery rate adjusted $q < .05$. MTG = middle temporal gyrus; vIFG = ventral inferior frontal gyrus.

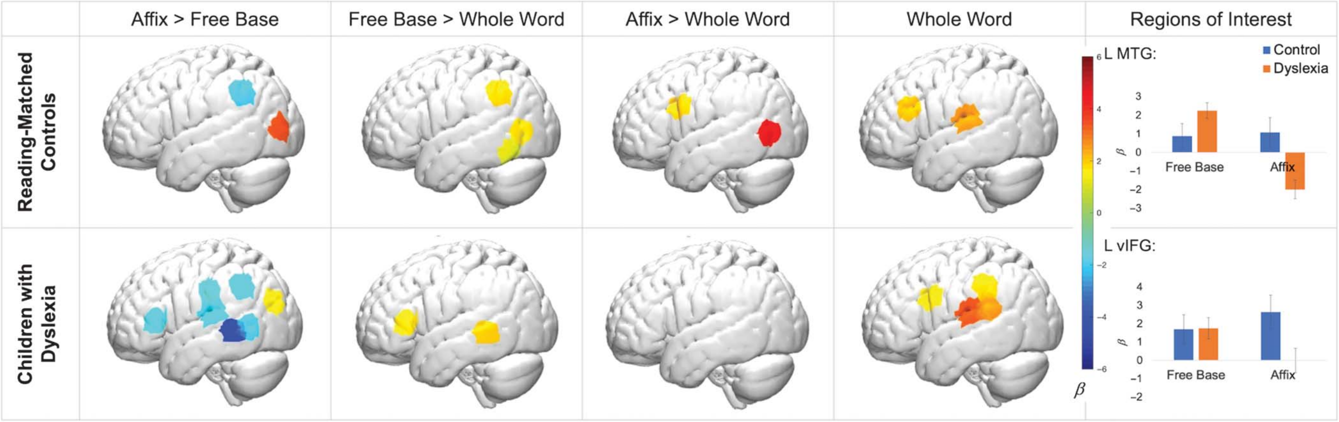
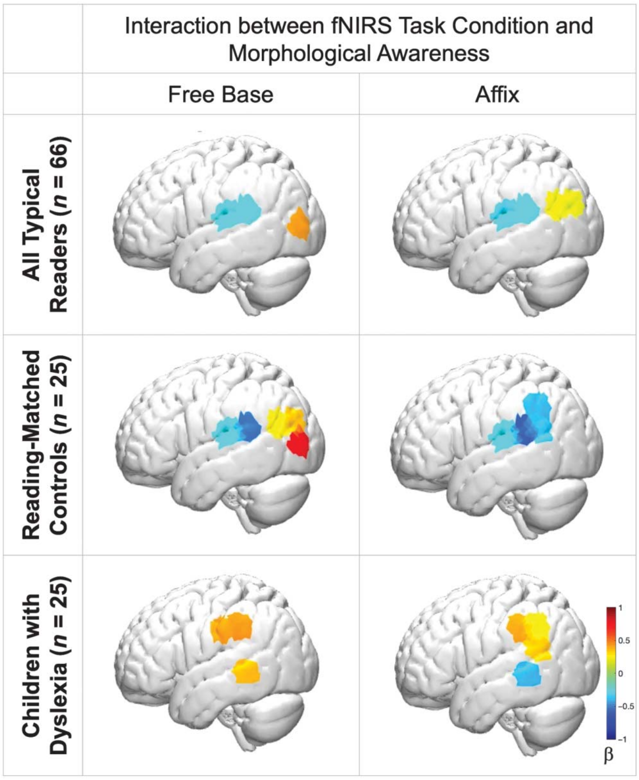


Figure 3. Brain-behavior associations between morphological awareness behavioral task performance (Early Lexical Morphology Measure) and activation during the morphological awareness neuroimaging task (FDR adjusted $q < .05$). fNIRS = functional Near Infrared Spectroscopy.



works on the neurobiology of reading have focused on comparisons of phonological and semantic subprocesses of word recognition (Booth et al., 2007; Landi et al., 2010). In the present study, we shifted the inquiry from more neutral semantic or meaning-based paradigms (e.g., seeing or hearing one word at a time and deciding if the word represents a living or nonliving entity; Rueckl et al., 2015) to a more focused inquiry of lexical morphology. Our first step was therefore to uncover differences and similarities between lexical morphology and phonological processes.

To accomplish the goal of Study 1, we used auditory phonological and morphological tasks with two levels of complexity (PA: onset-rime, onset-phoneme; MA: free base, affix). Children exhibited similar performance at each level of complexity across the two tasks (phonology and morphology). Nevertheless, at each complexity level, children showed stronger activation of left frontal and temporoparietal language networks during the morphology relative to phonology conditions (free base vs. onset-rime; affix vs. onset-phoneme). This greater activation for morphology than phonology was generally the case for both phonological and semantic neural networks (see Figure 1), a finding that is consistent with the view of morphology as a "binding agent" that connects words' sound and meaning representations (Kirby & Bowers, 2017).

Our finding that both morphology conditions elicited greater phonological network activation than the phonology task is especially striking given the phonological overlap among all three words in each morphology trial. One possible explanation may stem from the effort required for participants to simultaneously consider the morphological target and the phonological distractor (e.g., *animate* in *teammate – classmate – animate*). Deacon and Bryant (2006) found that phonological primes are almost as effective as morphological primes in supporting children's spelling. It is therefore possible that the stronger activation along the phonological pathway during the morphology task (relative to the phonology task) stems from the effort required to inhibit the phonological distractor when considering words' morpho-phonological compositions.

Gwilliams' neurocognitive view of morphology posits that free base recognition likely engages STG and MTG regions associated with segmenting words and matching these segments to their meanings, respectively. Recognizing derived words may additionally require the synthesis of these segments into an analytically complex whole, which is likely to engage the left IFG. Our developmental findings obtained with an auditory task are partially consistent with these predictions. A direct comparison between the two morphology conditions revealed stronger left temporoparietal activation during the affix relative to the free base condition. This finding likely reflects the greater structure-based analyses required to process more semantically abstract and rule-governed derived words. Intriguingly, we found the opposite pattern in children with dyslexia, which we will address in our discussion of Study 2.

The findings did reveal stronger left IFG activation during morphology than phonology conditions, which is generally consistent with the idea that morphological segmentation may be more analytically challenging than phonological segmentation. Moreover, children's left IFG activation was comparable across the affix and free base conditions, whereas Gwilliams' model predicts stronger left IFG activation for derivational affix processes. Yet, this framework is based on proficient adult language speakers, whereas the current study focuses on young children. One possible explanation for our findings is that the comparable left IFG activation across lexical morphology conditions reflects ongoing developmental processes of frontal lobe specialization for language function during elementary school years (Enge et al., 2020).

Finally, left inferior temporal and parietal regions typically associated with orthographic processing were more active during the phonology and derivational affix conditions than the free base condition. One possible explanation for this finding is that these two conditions were more likely to engage sound-to-grapheme associations, even in the auditory modality, and even in beginning readers. This interpretation is consistent with prior findings showing that as reading proficiency increases, children become more likely to engage visual processing networks even during auditory tasks (e.g., Booth et al., 2004).

Study 2: Morphological Processing Differs in Dyslexia

To uncover underlying mechanisms of lexical morphology processing in dyslexia, we compared the performance and patterns of brain activation of children with dyslexia to a younger group of reading-matched controls during free base and derivational affix morphological processing. The experimental groups were intentionally matched on word reading. The resulting groups also performed comparably on other measures, including the neuroimaging task (see Table 1). A direct comparison between the two morphology conditions revealed that children with dyslexia had more robust activation during the free base than the affix condition across bilateral frontal, temporal, and parietal regions associated with language and cognitive processes (see Figure 2). This pattern differs from standard predictions for lexical morphology (e.g., Gwilliams, 2020) and our own observations for typically developing readers, who generally exhibited stronger activation during the affix relative to the free base condition (Study 1). The subset of typically developing readers in Study 2 showed a somewhat similar pattern, though across fewer regions, likely due to the lower sample size.

Analyses of each lexical morphology condition help to contextualize the overall findings. Relative to the whole-word control condition, reading-matched controls exhibited stronger left temporal activation for both morphology conditions and stronger left frontal activation for the affix condition. In contrast, children with dyslexia only exhibited stronger activation during the free base but not the affix condition. In fact, they had more activation for the whole-word control than the affix condition. This stronger activation for the free base condition in children with dyslexia occurred along the semantic network, including left ventral inferior frontal gyrus (vIFG) and MTG regions (see Figure 2). The region of interest analyses for left vIFG and MTG regions of the semantic network further revealed that the two groups only differed during the affix condition, with hypoactivation in children with dyslexia. In sum, as compared to reading-matched controls, children with dyslexia appear to have normative activation during the free base morphology condition, especially along the semantic network, and hypoactivation during the affix condition.

Free base lexical morphology, but not the affix condition, appears to yield robust engagement of the semantic networks of the brain in children with dyslexia. The two types of lexical morphology and their experimental manipulations differed in complexity along the dimensions of semantic transparency and analytical complexity. In the free base condition, children matched the meaningful morphemic bases, whereas in the affix condition, children matched the rule-governed affixes. The few prior neuroimaging works on lexical morphology in dyslexia used experimental manipulations that were more similar to our free base condition (e.g., match builder-build vs. corner-corn; Aylward et al., 2003; Cavalli, Colé, et al., 2017). Aylward et al. (2003) found hypoactivation in children with dyslexia relative to the age-matched controls who were also better readers, but these group differences may have stemmed from differences in children's reading abilities. In contrast, Cavalli, Colé, et al. (2017) found stronger and earlier left IFG activation in college students with dyslexia relative to controls, with groups that did not differ in task accuracy. They interpreted this as suggesting that readers with dyslexia place stronger reliance on the analyses of lexical morphology cues than neurotypical readers. In sum, it is possible that the processing of free base morphology is relatively intact in children with dyslexia, especially in relation to their current reading ability.

Our neuroimaging findings make a meaningful contribution to a growing body of research suggesting that individuals with dyslexia may rely more heavily on semantic information contained in words and morphemes because of their phonological difficulties (Rasamimanana et al., 2020; van Rijthoven et al., 2021, 2018). For instance, van der Kleij et al. (2019) found that children with dyslexia benefited more from semantic primes than typical learners during word reading. Moreover, children with dyslexia showed a positive association between semantic priming and reading proficiency.

The finding of hypoactivation in children with dyslexia during the affix condition is generally consistent with prior works that have found hypoactivation in children with dyslexia during phonology tasks, across both auditory and visual modalities (see Kearns et al., 2019, and Norton et al., 2015, for reviews). Our affix condition required morpho-phonological word segmentation that was more reliant on abstract units of phonology and grammar than otherwise required for the free base morpheme task. It is therefore possible that the hypoactivation in dyslexia is related to previously observed deficits of phonological and grammatical processing in poor readers (Cantiani et al., 2013).

Our finding of hypoactivation in children with dyslexia during the most complex condition in our experimental task, derivational affix, is also consistent with prior works examining the effect of task difficulty in dyslexia (Partanen et al., 2019; Pugh et al., 2008). For example, the findings in Partanen et al.'s (2019) fMRI spelling study suggested that poor readers had more widespread activation when completing the "easy" spelling condition (words with higher printed words frequency) relative to the "hard" spelling condition (words with lower printed word frequency). Researchers have interpreted these findings as suggesting that children with dyslexia do have emerging language and literacy networks, yet these networks function less efficiently during more complex language and literacy tasks (Pugh et al., 2008).

Brain-Behavior Associations

Brain-behavior associations further help to explain some of the divergent findings between typical readers and those with dyslexia (see Figure 3). Typically developing children (Study 1) and the subset of reading-matched controls exhibited negative associations between morphological competence and brain activation in bilateral temporal regions during both morphology conditions. In contrast, children with dyslexia showed positive brain-behavior associations in left temporoparietal regions, with just one positive association in the right parietal region for affixes. Negative STG activation in typical children may reflect the efficacy with which children can inhibit phonological distractors to better identify semantically related items in our experimental trials that included a morphological match and a phonological distractor. Notable in dyslexia are the positive left STG/parietal and negative left MTG associations for the affix condition. This finding suggests an opposite process in dyslexia as children may attempt to suppress relatively intact semantic processing to engage in the morpho-phonological segmentation of derived words. Positive left MTG activation in children with dyslexia during free bases may again reflect an increased sensitivity to semantic cues during this condition. Our findings suggest that even spoken word processing in dyslexia is relatively more reliant on semantic cues than in typical development, either due to phonologically based reading difficulties or as a general factor of the disorder.

Limitations

Language selection is one limitation of this work. For instance, word structure in character-based languages differs in a way that requires a separate consideration that exceeds the scope of this study. The majority of words in Chinese are free base compounds (e.g., *class* + *room*), and lexical morphemes map onto characters. Morphological deficits, including those of lexical compounding, are a key characteristic of dyslexia in Chinese. Most importantly, the rules of compounding in Chinese are multifold more complex than in Indo-European languages such as English (McBride et al., 2022). It is, therefore, possible that our findings are generally consistent with those offered by researchers of dyslexia in Chinese. For instance, an event-related potential visual priming study of Chinese-speaking children with dyslexia observed an impaired response during morphological primes (e.g., classroom–bedroom; Tong et al., 2014). In Chinese, lexical compounding and not derivational morphology is a rule-governed process that requires complex analyses of word structure. Word structure analyses may therefore be a source of vulnerability across languages.

Another limitation of this work is the use of experimental conditions in which words in the free base trials may be more semantically associated than words in the derivational affix condition, due to the nature of these two types of lexical morphemes. Future research that accounts for semantic association, including priming studies (e.g., Quémart et al., 2018), may help to disambiguate some of the effects observed in the present work. Finally, we were limited to two tasks and two types of MA, only measured in the auditory modality. We also recognize that our sample was relatively homogeneous and mid-to-high socioeconomic status, limiting the generalizability of our findings.

Conclusions

The present study uncovers underlying mechanisms of lexical morphology in typical development and dyslexia. Our findings suggest that free base morpheme processing might be a source of resilience and strength for learning to read with dyslexia, whereas affix processing appears to be at risk in a way that is similar and potentially related to phonological deficits in dyslexia. Children with dyslexia may therefore benefit from additional support when learning derivational morphology. Lexico-semantic processing, in contrast, may be intact and therefore serve as a source of strength in learning to read with the disorder.

Author Contributions

Rachel L. Eggleston: Conceptualization (Equal), Formal Analysis (Lead), Investigation (Equal), Writing – original draft (Lead), Writing – review & editing (Lead). **Rebecca A. Marks:** Conceptualization (Equal), Formal Analysis (Supporting), Investigation (Equal), Writing – original draft (Supporting), Writing – review & editing (Supporting). **Xin Sun:** Conceptualization (Supporting), Investigation (Supporting), Writing – review & editing (Supporting). **Chi-Lin Yu:** Formal Analysis

(Supporting), Investigation (Supporting), Writing – review & editing (Supporting). **Kehui Zhang:** Investigation (Supporting), Writing – review & editing (Supporting). **Nia Nickerson:** Investigation (Supporting), Writing – review & editing (Supporting). **Xiaosu Hu:** Formal Analysis (Supporting), Software (Lead), Writing – review & editing (Supporting). **Valeria Caruso:** Formal Analysis (Supporting), Writing – review & editing (Supporting). **Ioulia Kovelman:** Conceptualization (Equal), Supervision (Lead), Funding acquisition (Lead), Writing – original draft (Supporting), Writing – review & editing (Supporting).

Data Availability Statement

Our data are available on the Deep Blue Data repository hosted by the University of Michigan Library (https://doi.org/10.7302/kxgf-ps11). This study was not preregistered.

Ethics Approval Statement

This study was approved by the Institutional Review Board at the University of Michigan.

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