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Morphological segmentation of nonwords in individuals with acquired dyslexia

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ABSTRACT

The current study investigated the influence of morphological structure in nonword reading in a case series of individuals with acquired dyslexia following brain damage. The aim of the study was to test the separate influence of embedded stems and suffixes on reading skills by comparing four different types of complex nonwords: stem + suffix (e.g., *nightness*), stem + non-suffix (e.g., *nightlude*), non-stem + suffix (e.g., *nishtness*), and non-stem + non-suffix (e.g., *nishtlude*); and two types of words: suffixed (e.g., *baker*) and non-suffixed (e.g., *diamond*). We report five individuals with excellent word reading skills, including no difficulties in reading morphologically complex words, but who had difficulty in reading nonwords. Nonword reading skills drastically improved when the nonwords were composed of a real stem compared to a non-stem, or a real suffix compared to a non-suffix. In one of the individuals (RF), a significant stem-by-suffix interaction was observed, suggesting that they additionally benefited when letter-strings were decomposable into two morphemes. Another individual's reading (SH) was facilitated by the presence of suffixes, but not by the presence stems. The impact of morphological structure on nonword reading, clearly observed in all five individuals, points to a pre-lexical activation of morphemes during reading. The results suggest that complex word reading involves three dissociable mechanisms: whole word processing, phonological decoding, and pre-lexical morpheme activation.

Introduction

One of the primary tools for uncovering the cognitive mechanisms that underlie our ability to read aloud has been the careful investigation of associations and dissociations with cognitive neuropsychological case studies of individuals with acquired dyslexia following brain damage. Making sense of how the reading system might be structured, so that it can be damaged in different ways to give rise to this diversity of reading impairments, has been a major contributor to theory development. As useful as cognitive neuropsychology has been for developing theories of reading aloud, research has largely focused on uncovering the cognitive mechanisms involved in the reading of morphologically simple words (e.g., *paint*). Morphologically complex words (e.g., *painter*) have not been studied as widely, and as a result, the cognitive underpinnings of complex word reading are still much less understood. The aim of the present study was to bridge this gap by conducting a series of case-studies to examine morphological processing in individuals with acquired dyslexia. We begin with a brief summary of some of the key theoretical advances of the field concerning morphologically simple words, and then explain how our study aims to move towards an extension of existing reading theories to capture mechanisms of complex word reading.

Amongst the most widely established pattern of findings in the cognitive neuropsychology of reading is the double dissociation between lexical and non-lexical reading (Coltheart, 1985). Lexical reading reflects the process of activating and retrieving words from the orthographic lexicon. Non-lexical reading reflects the process of mapping letters onto sounds using grapheme-to-phoneme correspondences. Lexical reading is necessary for reading irregular words, whereas non-lexical reading is necessary for the pronunciation of nonwords. According to the dual route cascaded (DRC) model of reading aloud, there are at least two separate pathways involved in forming the pronunciation of letter strings (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). The lexical route is responsible for retrieving whole-word representations from the orthographic lexicon and its selective damage results in impaired irregular word reading, i.e., surface dyslexia (e.g., Coltheart, Masterson, Byng, Prior, & Riddoch, 1983; Patterson, Marshall, & Coltheart, 1985). The non-lexical route is responsible for mapping

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letters onto sounds and its selective damage results in impaired nonword reading, i.e., phonological dyslexia (e.g., Berndt, Haendiges, Mitchum, & Wayland, 1996; Caccappolo-van-Vliet, Miozzo, & Stern, 2004; Coltheart, 1985; Derousné & Beauvois, 1985). As such, the DRC model's dual mechanism for lexical and non-lexical reading can account for the observed double dissociation between phonological dyslexia and surface dyslexia. Within the lexical pathway, a further subdivision has been proposed between a lexical semantic route and a lexical non-semantic route (e.g., Blazely, Coltheart, & Casey, 2005; Coltheart, Saunders, & Tree, 2010). In the lexical semantic route, whole-word representations from the orthographic lexicon are mapped onto semantic representations of meaning, which in turn are mapped onto whole-word representations in a phonological lexicon. In the lexical non-semantic route, orthographic lexicon representations can map directly onto phonological lexicon representations, without being mediated by the semantic system. Evidence for this dissociation comes from the observation that some individuals with severe semantic impairments, like individuals with semantic dementia, can still read aloud irregular words correctly, without knowing the meaning of those words (e.g., Playfoot, Billington, & Tree, 2018).

Another type of reading aloud models that have been continuously developed over the past few decades are connectionist models, which originally evolved from the triangle model (Seidenberg & McClelland, 1989). These models consist of a single mechanism which learns about regularities between orthography, phonology, and semantics. In these models, words and nonwords differ in their relative reliance on phonological and semantic representations. Both words and nonwords rely on phonological representations, but words are more reliant on semantic representations. Phonological dyslexia is assumed to be caused by an impairment of phonological information, rather than grapheme-phoneme conversion (e.g., Harm & Seidenberg, 1999; Harm & Seidenberg, 2001), whereas surface dyslexia is assumed to be caused by an impairment of semantic information (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996).

The cognitive neuropsychology of complex word reading

Many decades of research have focused on contrasting different types of monomorphemic words, such as regular (e.g., *cat*) and irregular words (e.g., *yacht*), and monomorphemic nonwords (e.g., *nep*). In contrast, cognitive neuropsychological investigations of polymorphemic word reading are sparser, and to this date no consensus has been reached as to how exactly morphological processing is implemented within a model of reading aloud. The DRC model simply is not constructed to model how polymorphemic words are read. Connectionist models also do not include any morphological representations per se, and instead suggest that morphological effects in written word processing tasks are a by-product of the correlations between orthography, phonology, and semantics (e.g., Gonnerman, Seidenberg, & Andersen, 2007; Harm & Seidenberg, 1999, 2004; Seidenberg & Gonnerman, 2000). However, such an approach is unlikely to capture the subtleties of morphological effects in word reading. For example, although connectionist models are able to simulate graded semantic and phonological similarity effects in morphologically complex words (e.g., Gonnerman et al., 2007), they fail to account for the kind of faciliatory priming effects that are typically observed for targets preceded by primes with a semantically opaque morphological structure (e.g., "corner-CORN"; Longtin, Segui, & Hallé, 2003; Rastle & Davis, 2008; Rastle, Davis, & New, 2004), suggesting that morphological processing applies independently of semantics to any letter-string with a morphological form structure (Beyersmann et al., 2016). After several decades of reading research, there are still no existing computational implementations of complex word reading that are able to account for the wide range of morphological phenomena.

While cognitive neuropsychological investigations of reading morphologically complex words are sparse, a number of cases have reported that morphological structure impacts the kinds of patterns of reading impairment observed following brain damage. Initial studies by Beauvois and Dérouesné (1979) and Patterson (1982), that were primarily focused on the reading of monomorphemic words, discovered that individuals with acquired dyslexia made morphological errors that share the same word stem with the target word, but have an added affix (e.g., *love* → *loved*), a deleted affix (e.g., *older* → *old*), or substituted affix (e.g., *walker* → *walking*), also known as "morphological paralexias". Although these studies appeared to provide some initial evidence for morphological processing in these participants, the investigators' interpretation of morphological paralexias has been criticized, as morphological errors may simply be a by-product of the visual similarity between the target word and the erroneous response (Funnell, 1987). More systematic investigations have demonstrated that at least some individuals with acquired dyslexia produce morphological errors even when visual similarity is controlled for across conditions.(e.g., Badecker & Caramazza, 1987, 1991; Castles, Coltheart, Savage, Bates, & Reid, 1996; Hamilton & Coslett, 2008; Job & Santori, 1984; Kay, 1988; Patterson, 1980; Rastle, Tyler, & Marslen-Wilson, 2006). For instance, Castles et al. (1996) reported data from an individual with acquired phonological dyslexia who had an impairment in reading complex words with a genuine morphological structure (e.g., *farmer*) compared to words with a pseudo-morphological structure (e.g., *corner*). A similar pattern was observed by Hamilton and Coslett (2008) in two individuals with acquired phonological dyslexia. These data do not only rule out the criticism that morphological paralexias are simple visual errors, but further suggest that the reading deficit in these individuals occurred at a post-lexical or "morpho-semantic" level responsible for the morphological decomposition of genuinely affixed word forms like *farmer*.

Another point of focus in the study of complex word reading has been the reported double dissociation of the processing of regularly (e.g., *drop* - *dropped*) and irregularly inflected words (e.g., *sleep* - *slept*). Some individuals with aphasia (typically those with agrammatic speech and left frontal lesions; see Ullman et al., 2005) have been found to have an impairment in reading aloud regular English inflected forms compared with irregular inflected forms (e.g., Badecker & Caramazza, 1987, 1991; Hamilton & Coslett, 2008; Marin, Saffran, & Schwartz, 1976; Ullman et al., 1997; Ullman, Hickok, & Pinker, 1995). In contrast, other aphasics (typically those with word-finding difficulties and left temporal/temporo-parietal lesions; see Ullman et al., 2005) have been shown to have a deficit in reading irregular inflections compared with regular inflections (e.g., Miozzo, 2003; Ullman et al., 2005).

What these prior findings seem to suggest is that the processing of affixed words (including regular inflections) is handled by a mechanism that is clearly distinct from the process of retrieving monomorphemic words and irregularly inflected words from the lexicon. Within the context of the DRC framework, it is possible to assume that irregularly inflected words can be retrieved via the lexical pathway, whereas regularly inflected and derived words are handled by the non-lexical pathway. Indeed, the case study by Castles et al. (1996) showed that a morphological parsing deficit coincided with a severe phonological impairment (i.e., a nonword reading deficit). A correlation between morphological and phonological processing is also predicted by the triangle model, which assumes stronger reliance on semantic processing for irregular inflections and stronger phonological processing for regular inflections (Bird, Lambon Ralph, Seidenberg, McClelland, & Patterson, 2003; Joanisse & Seidenberg, 1999; Patterson, Lambon Ralph, Hodges, & McClelland, 2001). These accounts are challenged, however, by studies showing that a deficit in reading regular inflections can occur in individuals *without* a phonological impairment (e.g., Hamilton & Coslett, 2008; Tree, 2008; Tree & Kay, 2006). For instance, Tree and Kay (2006) reported an individual with poor nonword reading ability whose performance was good on a variety of phonological tasks, making the possibility of a generalized phonologically based disruption unlikely. Indeed, Nickels, Biedermann, Coltheart, Saunders, and Tree (2008) suggest that no single locus of impairment (neither phonological nor non-lexical), but rather different combinations of impairment, can account for the reading deficits in individuals with phonological dyslexia. These findings show that although prior studies have been able to dissociate morphological from visual processing, the processing of regular from irregular inflected words, and nonword reading from a generalized form of phonological impairment, it is not clear if and how morphological processing can be dissociated from phonological decoding. What is needed to dissociate morphological and phonological processing are studies examining morphologically complex *nonwords*, which are discussed in the following section.

The cognitive neuropsychology of complex nonword reading

Cognitive neuropsychological investigations of the role of morphology in reading has largely focused on reading morphologically complex familiar words. Comparatively little work has focussed on the role of morphology in nonword reading (for evidence from children with dyslexia, see Burani, Marcolini, De Luca, & Zoccolotti, 2008). The examination of morphologically complex nonwords has several advantages. First, as is the case with all nonwords, including morphologically simple nonwords, participants cannot fall back onto a lexical reading strategy. Second, given that nonwords are not represented at the level of the orthographic lexicon, they represent the perfect tool to investigate sub-lexical reading mechanisms. Third, nonword materials are easy to select and can be more easily matched across conditions. Fourth, as we outline in more detail below, morphologically complex nonwords can be used to determine the unique contribution of stems and suffixes. In the present study, the latter aspect was achieved by using a tightly controlled 2 × 2 experimental design to investigate the presence or absence of stems and suffixes.

To our knowledge, there is only one existing cognitive neuropsychological investigation of morphologically complex nonword reading by Caramazza, Miceli, Silveri, and Laudanna (1985). The authors examined two Italian-speaking individuals (AG and LB) with acquired dyslexia who had intact word reading skills but impaired nonword reading skills, i.e., a phonological decoding deficit. Participant LB is of particular interest to the present study, because this was the only one of the two individuals whose morphologically complex nonword reading ability was tested. LB was assessed on words and two types of nonwords: "legal" nonwords including a real stem (e.g., *chied* in *chiediva*) and "illegal" nonwords including a non-stem (e.g., *chiad* in *chiadiva*). The stems or non-stems were accompanied by either a real suffix (e.g., *iva*) or a non-suffix (e.g., *ova*), but these endings were not matched or evenly distributed, and therefore only formed a suggestive part of the analyses. LB read correctly 97.1% words, but only 57.7% nonwords. Crucially, reading accuracy differed depending on whether or not the nonwords included a real stem or a non-stem. LB pronounced 76% nonwords correctly when they included a real stem, but only 51% correctly when they included a non-stem. This selective difficulty in reading nonwords suggests that LB clearly benefited from the presence of embedded stems. The results did not reveal a clear difference between nonwords containing suffixes compared to non-suffixes, but given that the number of suffixed and non-suffixed items was small and not evenly balanced across conditions, these findings remain inconclusive. One possible interpretation of the stem advantage in LB's nonword reading accuracy is that there is a specific morphological processing component that remains accessible even if the non-lexical phonological encoding system is impaired. An alternative (non-morphological) explanation of the effect would be that LB was able to retrieve the representations and pronunciations of the embedded stems via the lexical pathway. The findings by Caramazza and colleagues do not allow us to distinguish between these two different alternatives, because the study's design did not clearly distinguish between exhaustively decomposable nonwords (e.g., stem + suffix combinations) and non-decomposable nonwords (e.g., stem + non-suffix combinations).

The present study

The goal of the present study was to run a more extensive investigation of morphological processing using a carefully balanced experimental design by building on Caramazza et al.'s initial findings. We used a 2 × 2 experimental design to test for the presence or absence of both stems and suffixes in nonword reading. Four types of complex nonwords were created, including a stem + suffix condition (e.g., *nightness*), a stem + non-suffix condition (e.g., *nightlude*), a non-stem + suffix condition (e.g., *nishtness*), and a non-stem + non-suffix condition (e.g., *nishtlude*). In addition to the four types of nonwords, participants reading aloud performance was assessed on a set of suffixed (e.g., *baker*) and non-suffixed real words (e.g., *diamond*).

Our study reports a series of case-studies of individuals with a phonological dyslexia profile, thus presenting a reading impairment comparable to LB. We further focused the study on those individuals whose word reading errors showed no influence of morphological structure, that is, they did not make morphological errors in reading and their performance was equivalent on reading matched morphologically simple and morphologically complex words. The logic behind this selection criteria was that we wanted individuals who could use morphological structure to support their word reading, so that we could investigate how they may or may not be able to use this same structure to support their nonword reading. Moreover, a large number of carefully selected words and nonwords were used to establish whether or not morphological processing does indeed constitute an independent component of the reading system. The prediction was as follows: if the degree of nonword reading impairment is sensitive to the morphological structure of the nonwords, this would suggest that the reading system is capable of using the identification of morpheme-sized units to support reading unfamiliar words, and furthermore, that this morphological parsing component is clearly distinct from the non-lexical reading route. In other words, we should find individuals who are impaired in their ability to map graphemes onto phonemes, but who have less severe difficulties in retrieving embedded morphemes.

Morphological processing was examined by testing the participants' ability to read nonwords with embedded real stems compared to non-stems (Stem-Effect; e.g., *nightness* vs. *nishtness*), as well as their ability to read nonwords with embedded real suffixes compared to non-suffixes (Suffix-Effect; e.g., *nightness* vs. *nightlude*). If participants benefit from both the presence of a stem and the presence of a suffix, this would predict a step-wise pattern of morpheme facilitation (Mousikou et al., 2020), with reading performance being most accurate in the stem + suffix condition, average in the stem + non-suffix and non-stem + suffix conditions, and the least accurate in the non-stem + non-suffix condition. However, if the presence of a Stem-Effect (as previously evidenced in LB) simply arises because embedded stems can be retrieved via the lexical pathway without any involvement from morphological parsing, we would expect to see higher levels of reading accuracy in the presence of a stem (i.e., in the stem + suffix and stem + non-suffix conditions), compared to a non-stem (i.e., in the non-stem + suffix and non-stem + non-suffix conditions), irrespective of the presence or absence of a suffix.

Method

Participants

A total of seven individuals with acquired dyslexia participated in this study. However, two individuals were excluded from further testing because they made morphological word reading errors. The remaining five participants were native speakers of English, including three monolingual and two bilingual speakers (see Table 1). The ages of the participants ranged from 49 to 84. All participants were assessed based on the Western Aphasia Battery (WAB) to examine the severity of their language deficit. The WAB yields a total score termed the Aphasia Quotient (AQ), representing a weighted composite of performance on 10

Table 1
Demographics of participant sample, including the Western Aphasia Battery (WAB) Aphasia Quotient (AQ) for each participant.

Initials	Age	Education	Profession	Years post stroke	WAB AQ	Languages
GA	84	PhD	Microbiologist	1 year	99.6	English monolingual
JS	68	BA	Pharmaceutical Representative	3 years	75.2	Spanish-English bilingual
RF	49	MA	Physical Therapist	5 years	72.4	Norwegian-English bilingual
RT	72	MA	Coach & science teacher	3 years	93.8	English monolingual
SH	65	MA	ESL professor	1 year	96.2	English monolingual

separate WAB subtests. The AQ revealed that the severity of our participants' language impairment ranged from moderate (51–75) to mild (76–above). Below we provide more detailed descriptions of background testing for each participant, from a larger battery of background neuropsychological testing.

Background neuropsychological testing

As a part of standardized background testing in the lab, all participants were given a series of tests related to different aspects of their language performance. We report performance on tasks most related to issues of reading aloud here, and the results are shown in Table 2.

First, given the proposed links between acquired phonological dyslexia and more general impairments in phonological processing, all five participants were administered a broader battery of phonological processing task. In the minimal pair discrimination task, participants heard two syllables (either vowel-consonant or consonant–vowel) and had to decide if they were the same or different, where the syllables differed in the different trials by a single phonological feature. All participants were administered tests in which the difference was in the consonant and in which the difference was in the vowel (216 trials total). Across the board, all participants scored 90% correct or higher on this task (GA: 194/216, 90%; JS: 203/216, 94%; RF: 216/216, 100%; RT: 201/216, 93%; SH: 208/216, 97%), indicating good low-level perception of speech sounds. GA's performance on this task was the lowest of the group, though her performance was still fairly good. A possible explanation for this lowered performance is moderate hearing loss, as indicated by an audiogram, consistent with her advanced age. Phonological processing was further tested with a single-word, single-picture matching task (Martin, Lesch, & Bartha, 1999). In this task, a word was spoken and a picture was presented that was either the same as the target ("dog" – DOG), a phonological foil, ("dog" – LOG), a semantic foil, ("dog" – CAT) or an unrelated foil ("dog" – CAR), and the participant had to indicate whether or not they were the same or different. The same 54 spoken words were used in each condition, and the experiment was carried out over four separate testing sessions. All participants were 100% accurate when the foil was unrelated to the target and >95% correct for the matching trials. Critically, the participants rarely made errors on the phonological foil trials. GA, SH, and JS were all 100% correct on those trials, and RF and RT both made a single error. Taken together, these results indicate a good ability to extract phonological information from spoken words across all five individuals.

All five individuals showed worse performance with the semantic foils (GA: 50/54, 93%; JS: 44/54, 81%; RF: 42/54, 78%; RT: 51/54, 95%; SH: 48/54, 89%). This difficulty could either indicate difficulties in mapping from phonological forms onto meaning or impairments of semantic knowledge. To assess semantic knowledge, two tasks were administered; spoken vocabulary, as measured by the Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn, 2007) and Pyramids and Palm Trees Test (Howard & Patterson, 1992), a nonverbal test of semantics in which a participant had to select one of two competitor pictures that more closely matched a target picture. The PPVT is a standardized, normed test of vocabulary, and all five participants fell well within the distribution of neurotypical performance for age-matched adults (GA: 96th percentile, JS: 73rd percentile, RF: 45th percentile, RT: 30th percentile, SH: 64th percentile). Control range for the 52 item Pyramids and Palm Trees Test is 50–52 correct. GA (50/52), RF (51/52), and RT (51/52) were all within control range and JS (49/52) and SH (48/52) fell just below the cutoff. Therefore, it appears that all five participants had relatively intact semantic systems, suggesting that the relatively low performance with semantic foils in the single picture-single word matching task reflects a difficulty in mapping to semantics from spoken input.

Given that the current study focused on reading aloud, which engages aspects of the spoken production system, all participants were also administered the Philadelphia Naming Test, a 175 item confrontation naming task with simple black and white line drawings (Roach, Schwartz, Martin, Grewal, & Brecher, 1996). GA (169/175; 97%), RT (160/175; 91%), and SH (164/175; 94%) all performed within the control range on this task. JS (133/175; 76%) and RF (112/175; 64%) both were impaired in confrontation naming, and given their good performance on tasks of semantics, this difficulty emerged in either lexical-semantic mapping or phonological encoding. JS's errors were mostly semantically-related to the target (23/42 errors) or were no responses (10/42), indicating a difficulty in lexical-semantic mapping in

Table 2
Performance of the participant sample on background battery of language tasks. Participants were administered on a minimal pair discrimination task, a single-word, single-picture matching task (Martin et al., 1999), the Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn, 2007), the Pyramids and Palm Trees Test (Howard & Patterson, 1992), the Philadelphia Naming Test (PNT; Roach et al., 1996), and two sub-tests of the Psycholinguistic Assessments of Language Processing in Aphasia battery (PALPA; Kay et al., 1992).

Initials	Minimal Pair Discrimination	Single- Word, Single-Picture Matching				PPVT (percentile)	Pyramids & Palm Trees	PNT	PALPA 35		PALPA 36 (nonwords)
		Correct	Unrel.	Phon.	Sem.				Reg.	Exc.	
GA	194/216	54/54	54/54	54/54	50/54	96th	50/52	169/175	28/30	28/30	24/24
JS	203/216	54/54	54/54	54/54	44/54	73rd	49/52	133/175	28/30	28/30	14/24
RF	216/216	52/54	54/54	53/54	42/54	45th	51/52	112/175	13/30	18/30	4/24
RT	201/216	52/54	54/54	53/54	51/54	30th	51/52	160/175	21/30	24/30	3/24
SH	208/216	54/54	54/54	54/54	48/54	64th	48/52	164/175	29/30	27/30	2/24

speech production. RF's errors were more distributed, with the most common categories being semantically related errors (18/63 errors), no-responses (13/63 errors), but also phonologically-related nonword responses (12/63 errors), indicating additional difficulties in phonological encoding.

Finally, two standardized tests of reading aloud were administered from Psycholinguistic Assessments of Language Processing in Aphasia (PALPA; Kay, Coltheart, & Lesser, 1992). PALPA 35 includes 30 words with regular spellings and a matched set of 30 words with exceptional spellings. Greater accuracy with regular words than exception words is indicative of surface dyslexia. PALPA 36 includes 24 short nonwords, between 3 and 6 letters long, with highly consistent pronunciations in a normative sample. Worse performance on nonword reading than word reading is indicative of phonological dyslexia. GA, JS, and SH all performed well on the word reading task (all 56/60; 93%) and none showed effects of regularity (GA and JS were 28/30 for both word types, and SH was 29/30 for regular words and 27/30 for exception words). RT and RF made errors in reading words aloud. RT correctly read aloud 75% of the words (45/60), while RF only correctly read aloud 48% (29/60) of them. Critically, neither participant showed regularity effects (RT: Regular, 21/30; Exception, 24/30; RF: Regular, 13/60; Exception, 18/60). From this, we concluded that none of the participants in the sample had a pattern consistent with acquired surface dyslexia. In terms of nonword reading, JS (14/24; 58%), SH (2/24; 8%), RT (3/24; 13%), and RF (4/24; 17%) were all poor at this task, and performed worse than their word reading, indicating a pattern consistent with phonological dyslexia. Of note is that all four of these participants showed strikingly poor nonword reading despite relatively good phonological processing, contra the hypothesis that poor nonword reading and wider phonological impairments go hand in hand (see Tree, 2008; Tree & Kay, 2006 for a similar result). GA's reading of these short nonwords was unimpaired (24/24; 100%), though as will be shown below, her nonword reading starts to break down with longer strings.

For the purposes of the current study, the five participants were administered a battery of tasks designed to probe the effect of morphological structure on reading aloud, both tasks that included real words and a larger set of nonword stimuli. Below, we describe the structure of the stimuli used in these experiments.

Materials

The materials were adapted from a prior reading aloud study by Mousikou et al. (2020) that examined complex nonword reading in a cohort of unimpaired speakers. The experimental design included both words and nonwords (see Table 3). The list of word targets included thirty suffixed words (e.g., *baker*), and thirty non-suffixed words (e.g., *diamond*). All words were nouns and selected from the Celex database (Baayen, Piepenbrock, & van Rijn, 1993). For the purpose of creating the nonword targets, sixty morphologically-simple, frequent English nouns were selected (e.g., *night*). The selected nouns served as stems and were combined with a frequent suffix, forming nonwords in the stem + suffix condition (e.g., *nightness*), or a letter sequence that did not correspond to a suffix, forming nonwords in the stem + non-suffix condition (e.g., *nightlude*). To create the list of non-stems, a letter was replaced in the stems. The non-stems were combined with the suffixes, forming nonwords in the non-stem + suffix condition (e.g., *nishtness*), or the non-morphemic letter sequences, forming nonwords in the non-stem + non-suffix condition (e.g., *nishtlude*). For the stem + suffix and stem + non-suffix combinations, we ensured that the stem remained intact.

Table 3
Experimental design, examples, and item numbers per condition.

Condition	Example	N
Words		
Affixed	*baker*	30
Non-Affixed	*diamond*	30
Nonwords		
Stem + Suffix	*nightness*	60
Stem + Non-Suffix	*nightlude*	60
Non-Stem + Suffix	*nishtness*	60
Non-Stem + Non-Suffix	*nishtlude*	60

All items are listed in the Appendix and their psycholinguistic properties are shown in Table 4. Item frequencies were obtained from SUBTLEX-UK (Van Heuven, Mandera, Keuleers, & Brysbaert, 2014). As a lexical density index, we used OLD20 (Orthographic Levenshtein Distance; Yarkoni, Balota, & Yap, 2008). The four types of nonwords were matched on OLD20, number of letters, number of phonemes, and number of syllables (see Table 4).

Procedure

Each participant was presented with 300 items in two lists – 60 words and 240 nonwords – printed on paper, in two columns with between 15 and 20 rows. The items were randomized within each list and each participant received the same randomized list. Participants came in for a two-hour session once a week to read the stimuli until the task was finished. During the session, the stimuli were presented and the participant read each item aloud. Both an audio recording of their responses and a written version of their responses were made, though there were technical issues with the nonword recordings of JS. The audio recordings were later transcribed using the International Phonetic Alphabet (IPA) by a trained research assistant.

Results

Reading aloud responses for each participant were carefully screened and phonetically transcribed. All data, including the original recordings (except those of JS) and phonetic transcriptions, were uploaded into the study's Open Science Framework online repository (https://osf.io/4cf5j/). Phonetic stress has previously been shown to be an important indicator for morphological processing in disyllabic nonword reading (e.g., Ktori, Mousikou, & Rastle, 2018; Ktori, Tree, Mousikou, Coltheart, & Rastle, 2016; Rastle & Coltheart, 2000). However, due to the severity of the participants' nonword reading impairment, it was not possible to unambiguously assign stress to the phonetic transcription of the participants' nonword responses. We therefore had to refrain from stress assignment in the analyses reported below.

Response accuracy was coded in two steps. First, the responses of each participant were labelled as either correct or incorrect. To guide this process, the participants' responses were compared against the responses of 32 healthy, English-speaking adult controls who formed part of Mousikou et al. (2020)'s earlier sample. The responses of the healthy controls were phonetically transcribed by the same trained research assistant who also transcribed the participants' responses and are available via the online repository. Given that pronunciation variability is generally high (e.g., Coltheart & Ulicheva, 2018; Mousikou, Sadat, Lucas, & Rastle, 2017), we adopted lenient marking criteria, by which responses were only considered errors if they deviated from the range of responses given by the healthy controls and if they included clear mispronunciations (i.e., implausible grapheme-to-phoneme mappings). Responses were marked as correct when they included different plausible phonemic variations (e.g., [ˈblɒdfəl] and [ˈblʌdfəl] for *bloodful*), lazy phoneme drops at the end of the item (e.g., [ˈstɒpnɛp] instead of [ˈstɒpnɛpt] for *stopnept*), lazy phoneme drops at the end of a syllable (e.g., [ˈnɪʃnəs] instead of [ˈnɪʃtnəs] for *nishtness*), phoneme drops as a result of fast reading (e.g., [ˈmaʊsɚʌnd] instead of [ˈmaʊsɹʌnd] for *mouserund*), and phoneme insertions as a result of slow reading (e.g., [ˈɑɹəfeɪz] instead of [ˈɑɹfeɪz] for *arfase*). Second, the incorrect responses were screened for a range of error subtypes (see Table 5). The labelling of errors in the participant and healthy control data was completed by two

Table 4
Item descriptives for word and nonword stimuli (standard deviations in parentheses).

	Words		Nonwords			
	Suffixed	Non-Suffixed	Stem + Suffix	Stem + Non-Suffix	Non-Stem + Suffix	Non-Stem + Non-Suffix
OLD20	2.0 (0.6)	1.9 (0.7)	2.5 (0.5)	3.0 (0.7)	2.7 (0.6)	3.2 (0.7)
N letters	7.3 (1.5)	6.2 (1.5)	8.0 (1.3)	8.0 (1.2)	8.0 (1.3)	7.9 (1.2)
N phonemes	6.2 (1.9)	5.2 (1.4)	6.8 (1.2)	6.6 (1.1)	6.8 (1.2)	6.6 (1.1)
N syllables	2.4 (0.8)	1.9 (0.6)	2.1 (0.3)	2.1 (0.3)	2.1 (0.3)	2.1 (0.3)
Frequency (Zipf)	4.3 (0.6)	4.0 (0.7)	–	–	–	–

Table 5
Error sub-types, error type definition, and examples.

Error Type	Definition	Examples	
		Target	Response
First Component Error	Any error made within the first component (stem or non-stem)	*nishtness*	*nistness*
Second Component Error	Any error made within the second component (suffix or non-suffix)	*nightlude*	*nighttude*
Stem Substitution Initial Position	Substitution of the first component for another stem	*nishtness*	*nightness*
Stem Substitution Mid Position	Substitution of the mid-embedded letters for another stem	*bisfuitful*	*bisfruitful*
Stem Substitution Final Position	Substitution of the second component for another stem	*nightness*	*nightnice*
Suffix Substitution	Substituting the second component with another affix	*hallept*	*hallment*

of the authors (TA and EB).

Word reading

The overall accuracy analyses showed that all five participants had excellent word reading skills of over 80% accuracy (see Fig. 1). Word reading did not vary as a function of affix type (affixed vs. non-affixed). Given the high word reading accuracy across all participants, the error data were not further analyzed or subdivided into error subtypes.

Nonword reading

Healthy controls

Although error rates in the healthy controls were generally low (<3%), mean error rates varied across conditions, with the least in the two stem conditions (Stem + Suffix: 0.8%; Stem + Non-Suffix: 0.6%), average in the Non-Stem + Suffix condition (2.1%) and highest in the Non-Stem + Non-Suffix condition (8.0%). Analyses were performed using generalized linear mixed-effects models (Baayen, Davidson, & Bates, 2008) as implemented in the *lme4* package (Version 1.1.27.1; Bates, Maechler, Bolker, & Walker, 2015) in the statistical software R (Version 4.1.2, 2021-11-01, “Bird Hippie”, RCoreTeam, 2021). The significance of the fixed effects was determined with type III model comparisons using the *Anova* function in the *car* package (Version 3.0.12; Fox & Weisberg, 2019). The model included two effect-coded dependent variables (Stem [stem, non-stem] and Suffix [suffix, non-suffix]), their interaction, and random slopes and random intercepts for items and participants. There was a significant main effect of Stem ($\chi^2(2) = 9.66$, $p = .002$) and a significant main effect of Suffix ($\chi^2(1) = 4.01$, $p = .045$), but the interaction between Stem and Suffix was not significant ($\chi^2(1) = 0.19$, $p = .667$). All subtypes of errors were witnessed in the healthy control data, however only sporadically: the proportion of each error type was below 5%, and below 1.5% for morpheme substitutions, and therefore not further analyzed.

Reading impaired individuals

Given the focus on errors and error sub-types in the nonword analyses, all figures (except Fig. 1) display error rates instead of accuracy. The data of each participant were analyzed separately. Analyses were performed using generalized linear models (Dobson, 1990; Venables & Ripley, 2002) using the *glm* function as implemented in the statistical software R (Version 4.1.2, 2021-11-01, “Bird Hippie”, RCoreTeam, 2021). The generalized linear models included two effect-coded dependent variables (Stem [stem, non-stem] and Suffix [suffix, non-suffix]), their interaction, and a binomial link function. The independent variable varied depending on error type (e.g., first component errors were included as independent variable to analyze first component errors, second component errors were included as independent variable to analyze second component errors, etc.). In addition, to reduce the probability of making a Type I error, Bonferroni corrections were applied throughout the analyses to account for multiple comparisons (i.e., the level of statistical significance was adjusted to $p < .01$). The full model outputs can be viewed within the following Open Science Framework repository: https://osf.io/4cf5j/.

The initial nonword analyses included all errors, independently of error sub-types. The mean error rates per participant showed that the individual differed in their level of nonword reading impairment (mean error rates: SH: 16.8%; GA: 29.0%; JS: 61.3%; RF: 61.8%; RT: 70.2%), but all were severely impaired relative to the healthy adult controls (mean error rate: <3%). Most erroneous responses to nonwords were nonwords (for examples, see Table 5); only a small proportion (4.2%) were lexical errors (e.g., target: *hilement*; response: *helium*). The item *moot* was incorrectly classified as a non-stem and therefore removed from the analyses. The mean error rates for each participant are displayed in Fig. 2. There was a main effect of Stem which was significant for GA, JS, and RT (GA: $z = 2.64$, $p = .008$; JS: $z = 4.59$, $p < .001$; RT: $z = 5.28$, $p < .001$), but not significant for SH ($z = 2.23$, $p = .026$), showing that error rates were lower for stems than non-stems. The main effect of Suffix was significant for SH (SH: $z = 3.14$, $p = .002$), showing that error rates were lower for suffixes than non-suffixes, but not for GA, JS, and RT (GA: $z = 1.81$, $p = .071$; JS: $z = 1.84$, $p = .066$; RT: $z = 2.51$, $p = .012$). The interaction between Stem and Suffix was not significant GA, JS, RT, and SH (GA: $z = 1.56$, $p = .118$; JS: $z = 0.52$, $p = .601$; RT: $z = 1.15$, $p = .252$; SH: $z = 1.88$, $p = .061$). For RF, there was also a significant Stem-Effect ($z = 4.09$, $p < .001$), and a significant Suffix-Effect ($z = 3.61$, $p < .001$). In addition, the Stem-Suffix interaction was significant for RF ($z = 2.68$, $p = .007$), because the Suffix-Effect was bigger for stems than non-stems.[1]

To further explore the nature of errors, a set of more fine-tuned follow up analyses was performed for each participant. Errors were sub-divided into first component errors and second component errors. First component errors included all errors made within the stem or non-stem of each nonword. Second component errors included all errors

[1] An anonymous reviewer asked for a combined linear-mixed effects analysis including all five participants, which revealed a significant Stem-by-Suffix interaction across participants ($X^2 = 9.26$, $p = .002$). For a full model output, refer to the RMarkdown file deposited here: https://osf.io/4cf5j/. However, given well known issues in deriving in inferences about cognition from group-average neuropsychological data (Caramazza & McCloskey, 1988), we report individual level data analysis in the main text.

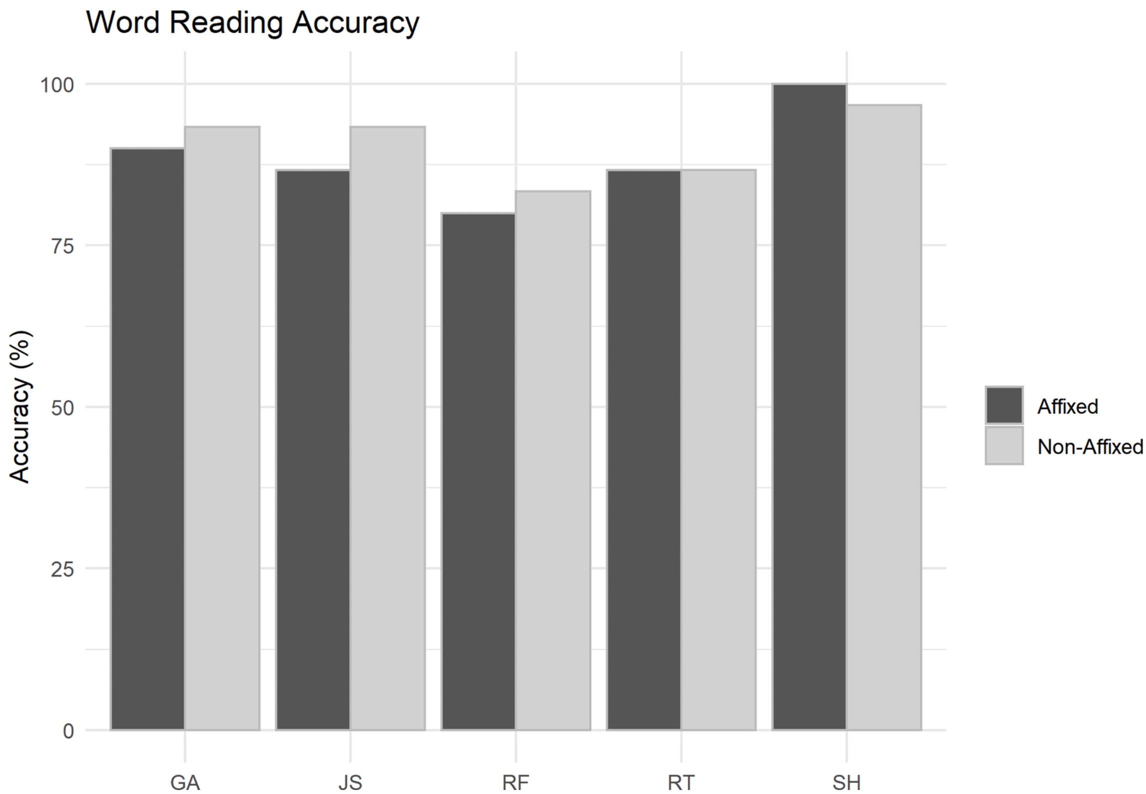

Fig. 1. Word reading accuracy (in %) for participants GA, JS, RF, RT, and SH, as a function of affix type (affixed, non-affixed).

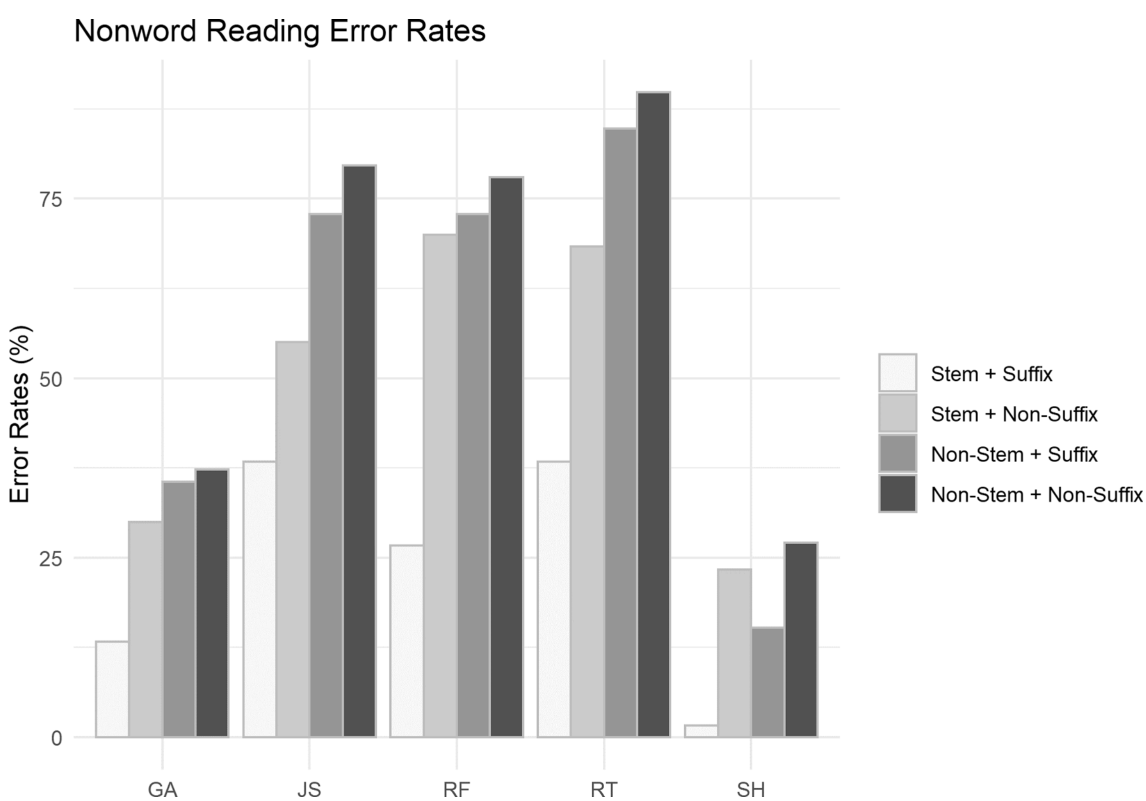

Fig. 2. Nonword reading error rates (in %) for participants GA, JS, RF, RT, and SH, as a function of stem type (stem, non-stem) and affix type (suffix, non-suffix).

made within the suffix or non-suffix of each nonword. The goal was to test if first component errors are more likely to occur for non-stems than stems, and if second component errors are more likely to occur for non-suffixes than suffixes. The results showed that this was indeed the case. In all five participants, the first component error analyses (see Fig. 3) revealed a significant main effect of Stem (GA: $z = 3.60, p < .001$; JS: $z =$

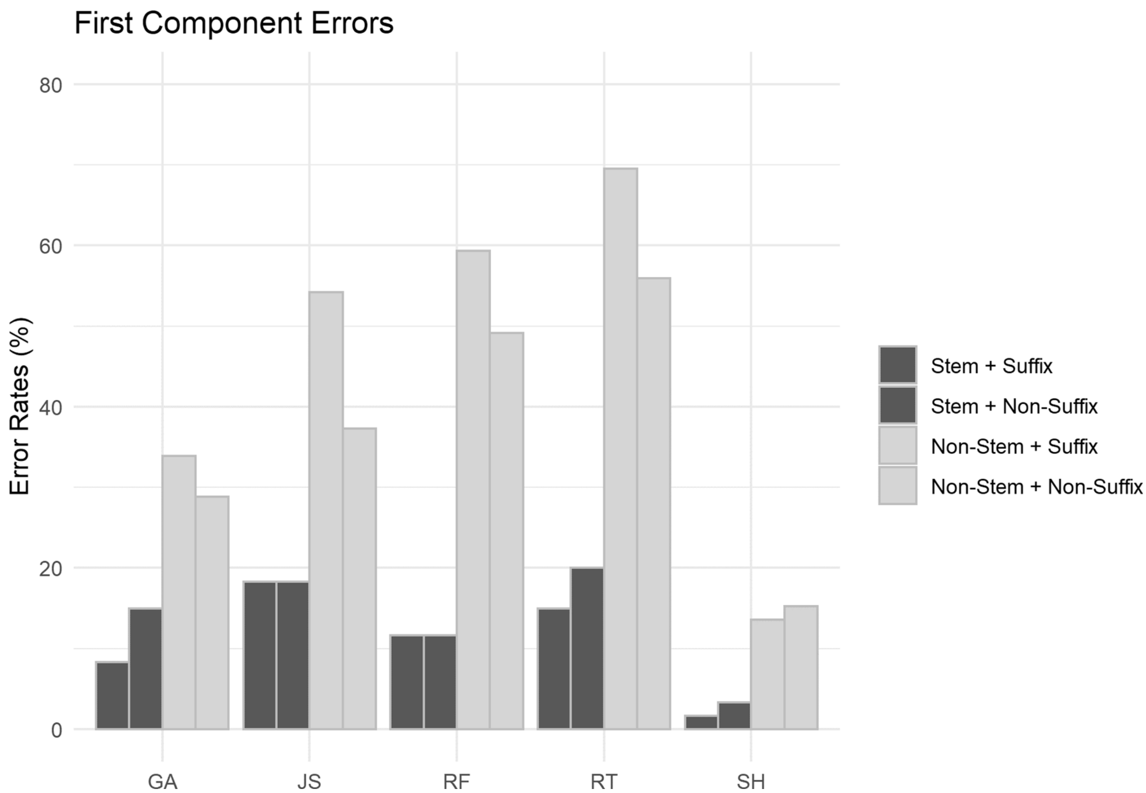

Fig. 3. First component error rates (in %) for participants GA, JS, RF, RT, and SH, as a function of stem type (stem, non-stem) and affix type (suffix, non-suffix). Across all five participants, the results revealed that first component errors rates were lower for embedded stems (black bars) than non-stems (grey bars).

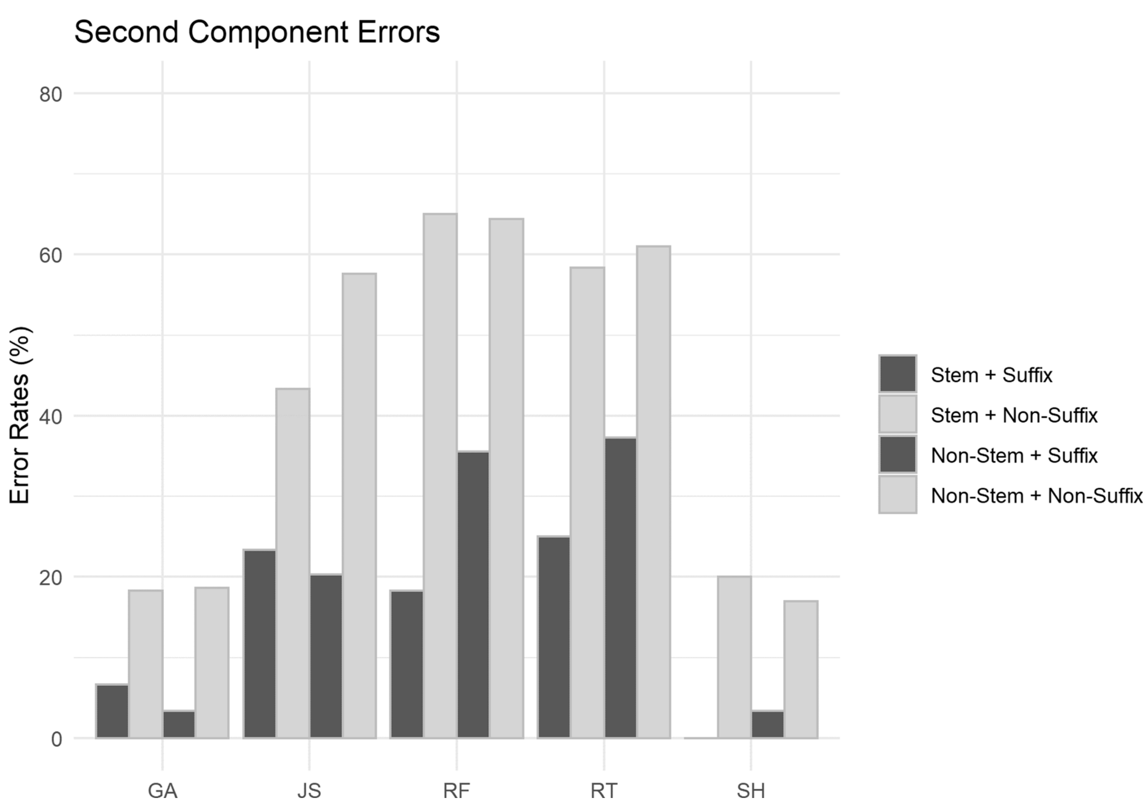

Fig. 4. Second component error rates (in %) for participants GA, JS, RF, RT, and SH, as a function of stem type (stem, non-stem) and affix type (suffix, non-suffix). In all participants, except SH, the results revealed that second component errors rates were lower for nonwords containing suffixes (black bars) compared to non-suffixes (grey bars).

4.38, p <.001; RT: z = 6.75, p <.001; SH: z = 2.88, p =.004; RF: z = 6.47, p <.001), showing that first component errors occurred less often for stems than non-stems. The main effect of Suffix was not significant (GA: z = 0.60, p =.549; JS: z = 1.14, p =.253; RT: z = 0.38, p =.703; SH: z = 0.63, p =.529; RF: z = 0.61, p =.545). The interaction between Stem and Suffix was not significant either (GA: z = 1.26, p =.206; JS: z = 1.14, p =.253; RT: z = 1.51, p =.132; SH: z = 0.43, p =.670; RF: z = 0.61, p =.545).

The second component error analyses revealed a similarly consistent pattern (see Fig. 4). In four participants, there was a significant main effect of Suffix (GA: z = 3.01, p =.003; JS: z = 4.48, p <.001; RT: z = 4.38, p <.001; RF: z = 5.72, p <.001), except in SH (z = 0.01, p =.989), showing that second component errors occurred less often for suffixes than non-suffixes. The main effect of Stem was not significant (GA: z = 0.69, p =.492; JS: z = 0.69, p =.489; RT: z = 1.26, p =.208; SH: z = 0.01, p =.991; RF: z = 1.52, p =.129). In none of the participants the interaction between Stem and Suffix was significant (GA: z = 0.73, p =.466; JS: z = 1.30, p =.194; RT: z = 0.85, p =.395; SH: z = 0.01, p =.991; RF: z = 1.61, p =.108).

To further explore the nature of first and second component errors, we conducted an additional set of analyses focusing on stem and suffix substitutions. A response was classified as a stem substitution when one component of the letter string had been replaced with another stem (see Table 5 for examples). A response was classified as a suffix substitution, if the second component of the letter string had been replaced with another suffix. Overall, the proportion of stem substitutions was high, whereas the proportion of suffix substitutions was low. Given that stem substitutions occurred in various positions of the letter string, they were subdivided into stem substitutions in initial position (SSIP), stem substitutions in final position (SSFP), and stem substitutions in mid-embedded position (SSMP). Across all five participants, SSMPs were below 5% and therefore not further analyzed.

In three of the five participants, the SSIP analysis (see Fig. 5) revealed a significant main effect of Stem (JS: z = 2.93, p =.003; RT: z = 5.64, p <.001; RF: z = 3.01, p =.003), suggesting that non-stems were more often substituted (e.g., substitution of *flish* with *fish* in *flishment* → response: *fishment*) than real stems (e.g., substitution of *park* with *dark* in *parkful* → response: *darkful*). In GA and SH, SSIP error rates were comparatively low (GA: 12.7%; SH: 2.5%) and did not reveal a significant Stem-Effect (GA: z = 2.05, p =.041; SH: z = 0.01, p =.994). The main effect of Suffix was not significant in any of the participants (GA: z = 0.78, p =.435; JS: z = 1.70, p =.090; RT: z = 0.23, p =.820; SH: z = 0.01, p =.995; RF: z = 0.75, p =.453). The interaction between Stem and Suffix was not significant either (GA: z = 1.34, p =.181; JS: z = 1.18, p =.238; RT: z = 1.60, p =.110; SH: z = 0.01, p =.994; RF: z = 1.44, p =.150).

The SSFP analyses revealed the exact opposite pattern of the SSIP analyses (see Fig. 6). In two of the five participants, there was a main effect of Suffix (JS: z = 3.92, p <.001; RT: z = 2.91, p =.004), showing that SSFPs occurred more often for non-suffixes (e.g., substitution of *ane* with *land* in *windane* → response: *windland*) than suffixes (e.g., substitution of *ness* with *nest* in *juiceness* → response: *juicenest*). The Suffix-Effect was not significant in GA, SH, and RF (GA: z = 1.99, p =.046; SH: z = 0.01, p =.990; RF: z = 2.45, p =.014). The main effect of Stem was not significant (GA: z = 0.83, p =.405; JS: z = 0.11, p =.915; RT: z = 0.96, p =.336; SH: z = 0.01, p =.991; RF: z = 0.60, p =.897). The interaction between Stem and Suffix was not significant (GA: z = 0.86, p =.390; JS: z = 0.68, p =.494; RT: z = 0.43, p =.670; SH: z = 0.01, p =.991; RF: z = 0.13, p =.897).

The number of suffix substitutions were generally low (<1% in GA and SH, ~10% in JS, RF, and RT) and did not yield any significant differences between conditions (all ps were larger than the Bonferoni corrected value of .01).

Discussion

The aim of the current study was to examine morphological processing in five individuals with acquired dyslexia. Each individual was

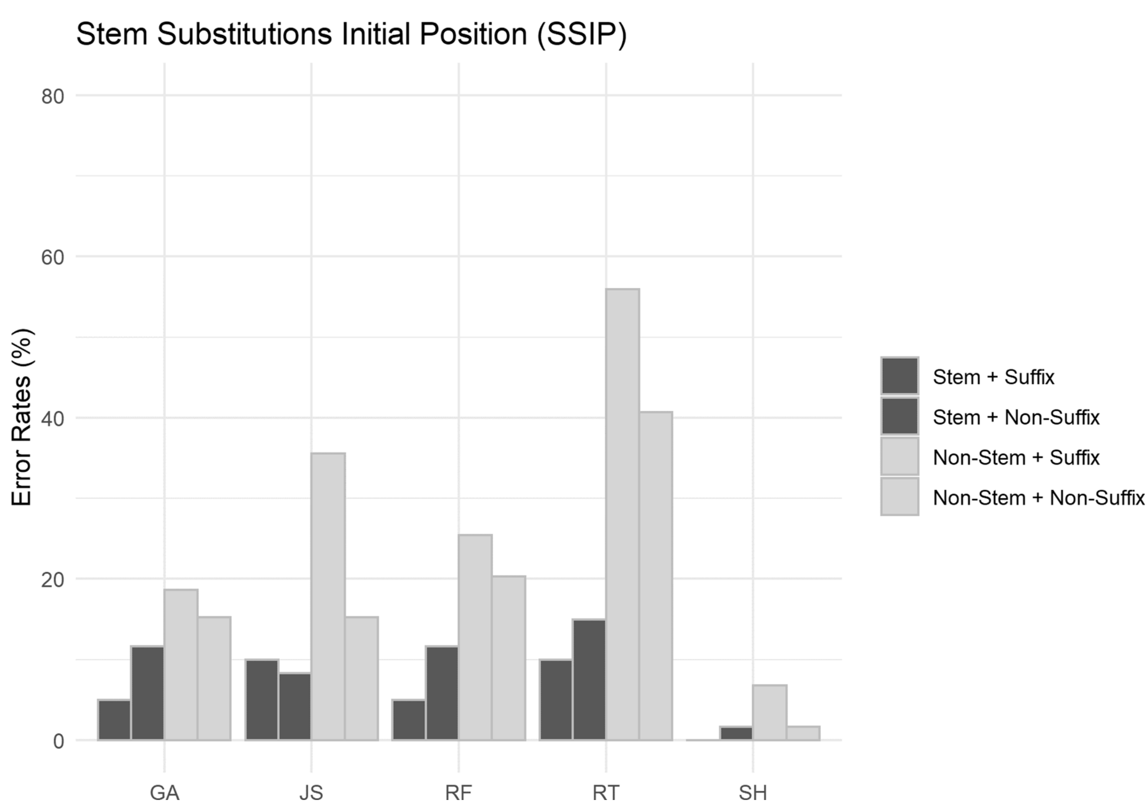

Fig. 5. Stem substitutions in initial position (in %), as a function of stem type (stem, non-stem) and affix type (suffix, non-suffix). Across all five participants, the results revealed that non-stems (grey bars) were substituted more often than stems (black bars).

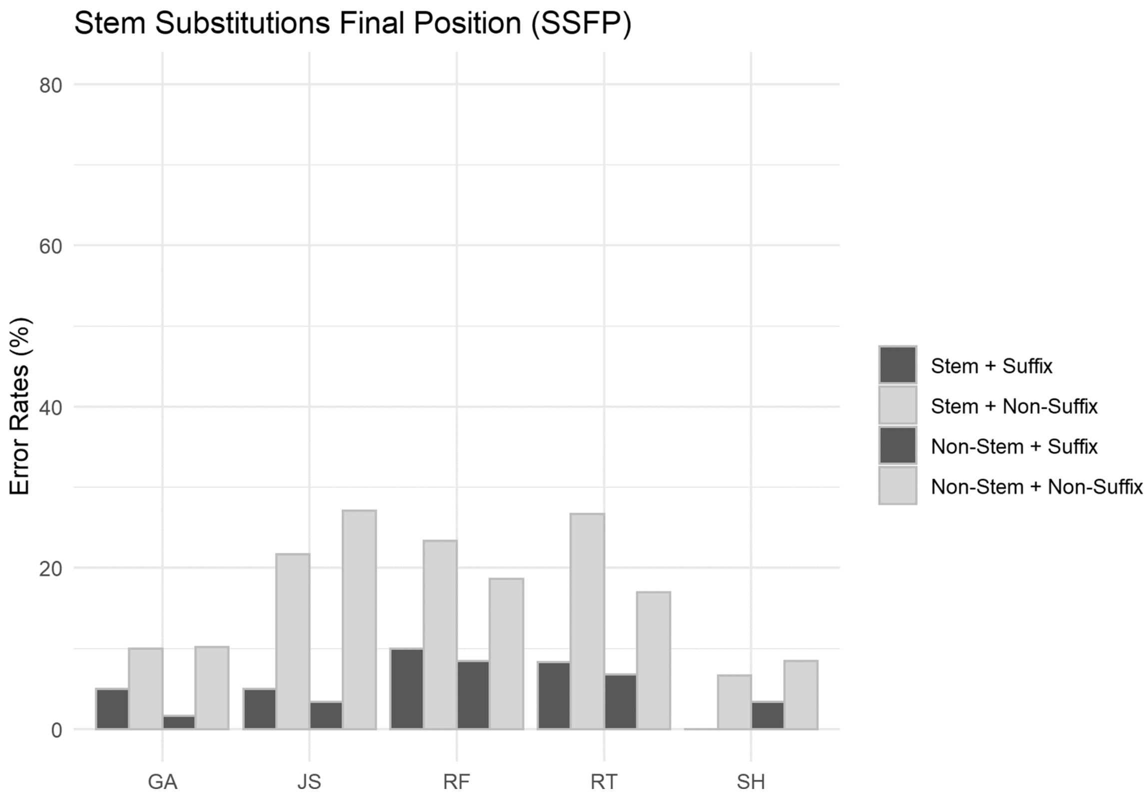

Fig. 6. Stem substitutions in final position (in %), as a function of stem type (stem, non-stem) and affix type (suffix, non-suffix). All five participants showed that non-suffixes (grey bars) were substituted more often than suffixes (black bars).

assessed on a battery of real words and nonwords. Items were presented individually and participants were asked to read out each item as accurately as possible. The real words were half affixed (e.g., *baker*) and half non-affixed (e.g., *diamond*). The nonwords were subdivided into four conditions to test the unique contribution of the stem and the suffix on participants' nonword reading skills: a stem + suffix condition (e.g., *nightness*), a stem + non-suffix condition (e.g., *nightlude*), a non-stem + suffix condition (e.g., *nishtness*), and a non-stem + non-suffix condition (e.g., *nishtlude*).

Individuals were identified to be part of the study because they performed well in word reading, and their word reading skills were not modulated by morphological complexity. In all five individuals, nonword reading skills were clearly impaired and constituted the central focus of the current investigation. The dissociation between intact word and impaired nonword reading skills is consistent with a reading pattern typically seen in individuals with phonological dyslexia. The nonword decoding difficulty points to a selective impairment of the non-lexical reading mechanism that is necessary to map letters onto sounds. Such a selective impairment has been previously accounted for by the dual-route model of reading (Coltheart et al., 2001), suggesting that phonological dyslexia is caused by specific damage to the non-lexical reading pathway, while leaving the lexical pathway intact. The here observed dissociation between word and nonword reading therefore provides further evidence for the two clearly distinct lexical and non-lexical reading mechanisms.

Below we summarize the key findings with respect to the role of morphology in reading aloud nonwords and discuss if and how morphological processing is captured within the reading system. Given that the primary source of errors came from reading nonwords rather than reading real words, the focus of the discussion is on the analysis of errors in the nonword data.

Morpheme facilitation

There was a robust morpheme facilitation effect in all participants in the study. The present study's experimental 2×2 design allowed us to clearly tease apart the independent roles of the stem and the suffix in nonword reading. The results showed that participants benefitted from both the presence of stems and suffixes, but to different degrees. Our study provides evidence for robust embedded stem activation in GA, JS, RF, and RT, showing that all of them found it easier to name nonwords including a real stem compared to a non-stem. In addition, there was evidence for suffix activation in RF, and SH, showing that these participants found it easier to name nonwords including a real suffix compared to a non-suffix (see also Burani et al., 2008, who observed a suffix faciliatation effect in dyslexic children). This pattern of results alone is intriguing, because despite the significant nonword reading deficit that was present across all participants, the presence of stems and suffixes clearly supported the process of nonword decoding.

The further subdivision of error into stem substitutions (SSIP, SSMP, and SSFP) and suffix substitutions revealed that one of the compensating mechanisms for nonword decoding difficulties in participants with acquired dyslexia is morpheme substitution. We interpret the morpheme substitutions as an attempt to map the embedded orthographic substructures onto existing morphemic representations. While stem substitutions occurred frequently across participants (with the exception of SH) and differed significantly across conditions, suffix substitutions were more sparse and less varied across conditions. One possibility is that stem substitutions were achieved by mapping letters onto existing lexical representations via the lexical pathway. Lexical processing was intact in all individuals in the sample, which may have served as a compensating strategy during nonword decoding. However, most erroneous responses to nonwords were nonwords, not words, suggesting that participants did not read nonwords via the lexical route. Therefore, a more likely explanation for the observed stem substitution effects is that it reflects the process of activating morphemes, rather than whole-word representations.

Stem substitutions occurred in both initial (SSIP) and final positions (SSFP), but hardly ever emerged in mid-embedded position (SSMP). This finding supports the idea that the positional decoding of embedded stems is guided by the principle of edge-alignedness (i.e., stem substitutions occurred more often in edge-aligned position than in mid-position). The principle of edge-alignedness is based on the idea that the spaces surrounding letter strings are used as anchor points for letter position encoding (Fischer-Baum, Charny, & McCloskey, 2011). It predicts that priority is given to stems embedded at the "edges" of the letter string (i.e., initial and final string position) compared to stems embedded in mid-position (e.g., Beyersmann & Grainger, 2022; Beyersmann, Grainger, & Castles, 2019; Beyersmann et al., 2018; Grainger & Beyersmann, 2017). The present data provide support for this idea, suggesting that the recovery of embedded morphemes was facilitated by the principle of edge-alignedness.

A further point of discussion concerns the differences in Stem- and Suffix-Effects that were observed between participants, who all came into the study with widely varied neuro-psychological profiles and who also differed in the severity of their reading impairment. Previously, it has been reported that the presence of morphemes facilitates nonword reading in healthy, English-speaking children and adults (Mousikou et al., 2020). Although the current study supports the notion of a morpheme facilitation effect in nonword reading, it goes beyond these earlier findings by suggesting that individuals with acquired dyslexia do not rely on the activation of stems and suffixes to the same extent. GA's, JS's, and RT's reading was facilitated by the presence of stems, but not by the presence of suffixes. RF's reading was facilitated by the presence of both stems and suffixes. SH's reading was facilitated by the presence of suffixes, but not by the presence stems. These results are difficult to explain within the context of a theoretical framework where one and the same morphological parsing mechanism is applied to all morphemic units, including stems and affixes, and instead support the idea that stems and affixes are likely handled by different components of the reading system. The here observed differences in stem and affix processing fit with the assumptions of the word and affix model (Beyersmann & Grainger, 2022; Grainger & Beyersmann, 2017), a point we return to in more detail below. What is worth noting is that SH stood out from the other participants, not only showing the clearest form of stem-suffix dissociation, but also lower overall error rates compared to the other participants, reflecting SH's milder degree of reading impairment. Also, a visual inspection of Fig. 2 revealed that while GA, SH, RF, and RT showed the predicted step-wise error pattern, SH demonstrated a drop in error rates in the two conditions containing suffixes (i.e., the stem + suffix and non-stem + suffix conditions), suggesting that they particularly benefitted from the presence of suffixes in their reading. This observation was supported by SH's logistic regression analyses, showing that while there was a significant Suffix-Effect, the Stem-, SSIP-, and SSFP-Effects were all non-significant, thus further highlighting differences in stem and suffix processing within the current sample. In sum, the variation in response patterns within the current series of case-studies shows how clinical findings are able to go beyond the experimental work within healthy populations as they allow for fine-tuned dissociations between the different components of the reading system.

Morphological full decomposition

The only participant that showed evidence for a significant Stem-by-Suffix interaction was RF, indicating that the Suffix-Effect was larger in the presence of a stem than a non-stem. The visual inspection of Fig. 2 showed that RF's response pattern was indeed, to some extent, comparable to the response pattern of the other participants, indicating that all five participants found it easier to read nonwords that were exhaustively decomposable into morphemes than those that were not.[2] What was particularly remarkable in RF is the robust difference in error rates to items that were exhaustively decomposable into morphemes (26.7% errors in the stem + suffix condition) compared to the rest (>70% errors in the other three conditions). This is noteworthy given that RF's nonword reading skills were the second most impaired in this group of participants (with an overall error rate of 61.8%, only surpassed by RT with a mean error rate of 70.2%), yet error rates were less than half in the stem + suffix condition, suggesting that this individual was able to use morphological processing to compensate for their nonword reading deficit.

RF's data therefore provide the strongest evidence in favor of a morpheme-specific parsing module that is entirely separate from the lexical and non-lexical pathways. Such a module has been proposed in the literature, based on the results of masked priming studies with highly literate adults (Amenta & Crepaldi, 2012; Rastle & Davis, 2008). Priming effects have been consistently reported for words that can be parsed into a stem and an affix, even in the absence of a semantic relationship between the prime and the target (e.g., *corner* – *CORN*), but not when the prime contains the target as an embedded word and a non-morphemic ending (e.g., *brothel* – *BROTH*). Based on these results, Rastle and Davis (2008) argue that prior to lexical access, strings of letters are decomposed into morphemes, but only if the decomposition results in a complete morphological parse of the input string. RF's data support this proposed parsing mechanism, as she only shows the benefit of morphological structure on nonword reading when a full parse is possible. The fact that the other individuals in this sample show morpheme facilitation and stem substitutions, even when the nonword cannot be parsed into a stem and suffix, suggests that this parsing mechanism is not the only way that morphological structure can influence reading aloud. Hence, these results point to the presence of three distinct processing mechanisms: lexical whole word processing, non-lexical phonological decoding, and morphological processing.

One explanation for the difference in response pattern across participants is that RF's level of reading impairment differed from the reading impairment of the other four participants. Although the Stem-by-Suffix interaction was not significant in GA, JS, RT, and SH's reading aloud data, they exhibited robust Stem- and Suffix-Effects. This raises the possibility that the activation of embedded stems and suffixes is handled by a different component of the reading system than morphological parsing per se. In fact, the recent word and affix model of visual word recognition by Beyersmann and Grainger (2022) assumes that the activation of embedded stems and affixes occurs via an entirely non-morphological process of mapping letter strings onto existing stem and affix representations in the orthographic lexicon (for an earlier version of the model, see Grainger & Beyersmann, 2017). According to this theory, reading does not only attempt to map letter strings onto whole-word lexical representations, but also recognizes embedded stems and affixes stored at the level of the orthographic lexicon. This explains why embedded stems are activated independently of whether they are embedded in an exhaustively decomposable nonword like *nightness*, or in a non-morphological nonword like *nightlude*. It also explains why suffixes are activated independently of whether they are embedded in an exhaustively decomposable nonword like *nightness*, or a non-morphological nonword like *nishtness*. In other words, although Beyersmann and Grainger's theoretical framework is focused on visual word recognition rather than reading aloud, the model's non-

[2] This observation is supported by post-hoc analyses using linear-mixed effects modeling across all five participants (for a full model output see https://osf.io/4cf5j/), showing a significant stem * suffix interaction when modelled across all participants.

morphological mechanism of morpheme activation provides an explanation of the robust Stem- and Suffix-Effects that were observed across all five individuals. The model further assumes an early pre-lexical mechanism of morphological full decomposition which is implemented in links between orthographic input and the orthographic lexicon. Morphological full decomposition is applied to any exhaustively decomposable letter string (e.g., *nightness*, but not *nightlude*, *nishtness*, or *nishtlude*). Successful decomposition results in an activation boost to the embedded morphemes, which explains RF's particularly accurate responses in the stem + suffix (*night* + *ness*) condition (see Fig. 2).

The representation of morphemes and whole words

A further point of discussion concerns the representation of morphemes and whole words within the mental lexicon. The word and affix model assumes that whole words and morphemes are both represented at the level of the orthographic lexicon. At least in the visual word recognition literature, there are no findings that would force the view that whole words and morphemes are stored separately. However, the current reading aloud data challenge the idea of a combined storage, because the majority of the participants' errors were nonwords which often included intact morphemes (e.g., target: *larkful*, response: *parkful*). If these responses were simple lexicalization errors, it would have resulted in whole word responses (e.g., *parking, eventful*, etc.) rather than nonword responses.

One solution to this problem is that the reading system stores morphemic representations separately (outside the orthographic lexicon). As such, morphemic stems would be represented twice: as specialized morphemic representations, as well as orthographic whole word representations. This would compromise the processing efficiency of the

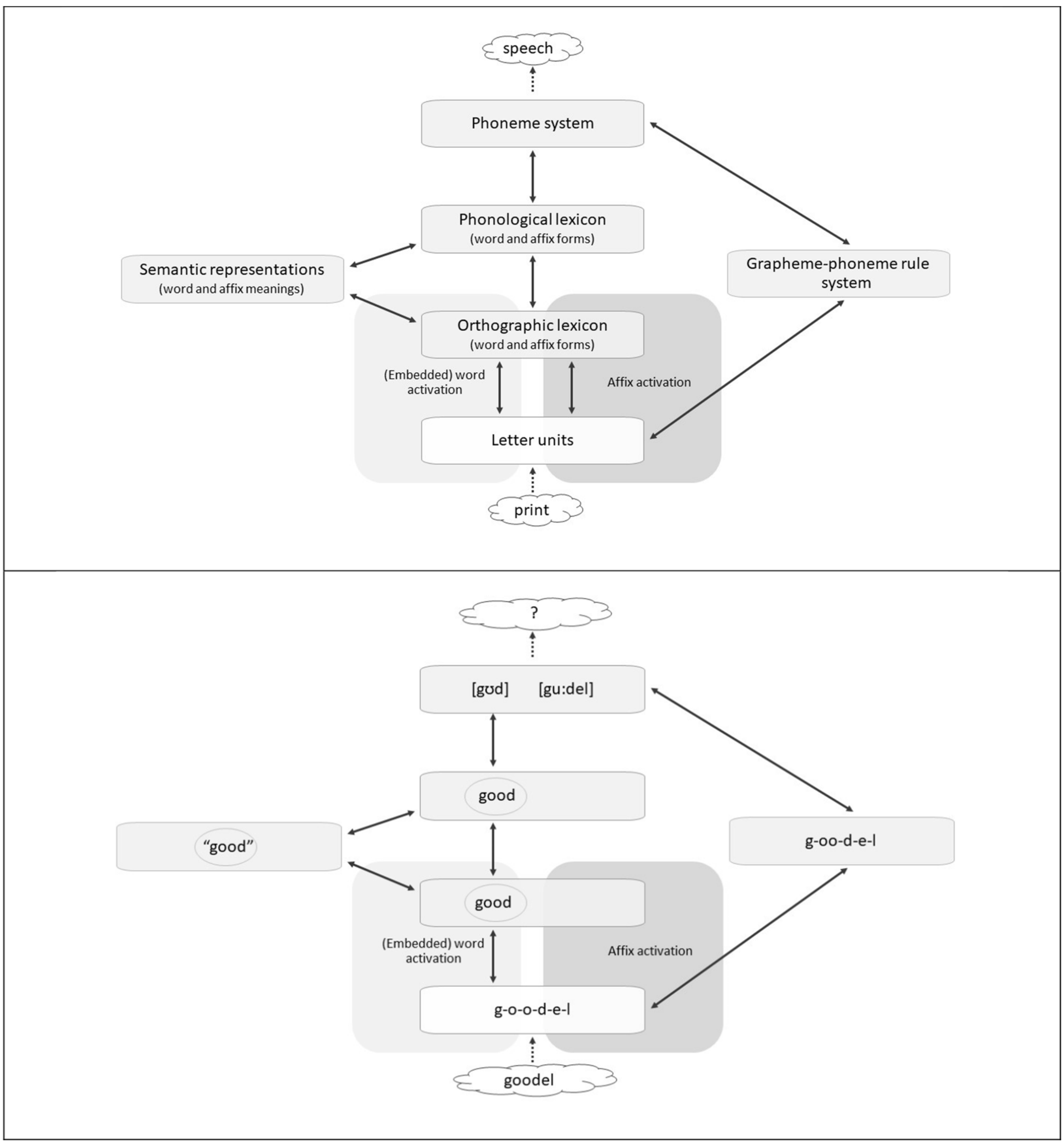

Fig. 7. A tentative model of complex word reading, based on the principles of the DRC model (Coltheart et al., 2001), capturing the challenges involved in implementing a system which merges both lexical and non-lexical components during reading aloud. The initial mappings between letter units and the orthographic lexicon are mediated by two key mechanisms, (embedded) word activation and affix activation, following the assumptions of the word and affix model (Beyersmann & Grainger, 2022). The top panel represents the model's basic building blocks. The bottom panel represents the conflict in pronunciations that can arise in the example of the nonword *goodel*, consisting of a phonologically irregular embedded word (*good*) and a non-morphemic ending (*-el*).

reading system and also be in direct contradiction with the assumptions of the word and affix model that embedded stems (with the exception of bound stems) are activated and represented in the orthographic lexicon just like any other free-standing word. Another possibility may be that morphemes and whole words are indeed stored within the same lexicon, but that the reading system is able to combine.

the pronunciations of embedded words and affixes (e.g., "night" + "ness") and those of embedded lexical units and nonsense letter strings (e.g., "night" + "lude"), by merging both lexical and non-lexical information.

A promising theoretical starting point might be extending the basic principles of the DRC model (Coltheart et al., 2001) to capture the mechanisms of complex word reading (Fig. 7). Although promising, this undoubtedly represents one of the most significant challenges for current models of reading. Earlier work by Rastle and Coltheart (2000) showed that the presence of affixes influences stress assignment in the reading of disyllabic words. The authors developed an algorithm for lexical and non-lexical print-to-sound translations of disyllabic words and nonwords, building on the idea that affixes can be used as cues to stress assignment (e.g., Fudge, 1984; Ktori et al., 2018; Ktori et al., 2016; Mousikou et al., 2017). The algorithm used an affix search mechanism to guide the placement of stress (see Rastle & Coltheart, 2000; Fig. 2) by drawing on a affix store as well as an additional set of orthographic rules that must be met. The results showed that the algorithm was able to account for a large proportion of stress pattern within disyllabic words, thus highlighting the important role of morphological structure in print-to-sound mappings. However, besides this important groundwork for poly-syllabic stress assignment, there are to our best of knowledge, no existing theoretical or computational models capturing the combined use of lexical and non-lexical reading mechanism within morphologically complex letter strings. This represents a major limitation, because as the current series of case studies demonstrates, embedded stem and suffix effects were robust across all five individuals and cannot simply be explained away as lexicalization errors.

Within the framework of the DRC model, one may therefore begin with the assumption that the orthographic lexicon comprises more than just whole words, but instead a combined storage of both word and affix forms. Similarly, the phonological lexicon would consist of a combined storage of word and affix forms, and the semantic representations would include both word and affix meanings (see top panel of Fig. 7). The tentative model depicted in Fig. 7 incorporates the notion of the word and affix model (Beyersmann & Grainger, 2022) that orthographic input is initially mapped onto the orthographic lexicon via two separate mechanisms: one that activates words that are embedded at both edges of the letter string and one that activates affixes in either initial (prefixes) or final position (suffixes). For example, for a nonword like *goodel* (see bottom panel of Fig. 7), the system would activate the embedded word *good* in the orthographic lexicon, which would in turn activate the representations of *good* in the phonological lexicon as well as at the level of semantics. In the final stage of the model, the lexical representation of *good* would then be mapped onto its lexical pronunciation "[gʊd]". Given the model's parallel nature, the grapheme-phoneme rule system would simultaneously map the letter units with corresponding phonemes, thus producing the non-lexical reading "[gu:del]". The system then merges the input from the lexical and non-lexical pathway at the level of the phoneme system (e.g., Hillis & Caramazza, 1991; Miceli, Capasso, & Caramazza, 1994; Ward, Stott, & Parkin, 2000). It is at this final stage of the model where things become complicated. In the example of *goodel*, the phoneme system is presented with two conflicting pronunciations ("[gʊd]" and "[gu:del]"), none of which correctly capture the embedded stem effect (i.e., spoken output form "[gʊdel]") which was so frequently observed in the current data. To solve this conflict, the phoneme system may apply a pronunciation correction of the initial part of the non-lexical pronunciation, although this idea remains speculative and will require more systematic future investigations. What exactly the mechanisms behind the pronunciation correction would be is unclear. Although the current version of the DRC model successfully captures the reading of monomorphemic words, including the dissociation between lexical and non-lexical reading, which was also clearly visible in the current participant data, the here presented approach remains underspecified. A further key challenge for future research involves incorporating prior evidence for the impact of morphological structure on the placement of phonemic stress (e.g., Ktori et al., 2018; Ktori et al., 2016; Mousikou et al., 2017; Rastle & Coltheart, 2000) within the current theoretical considerations. More experimental and computational modeling work is needed to further specify the mechanisms by which complex nonword reading is achieved. The present data highlight the important role of embedded stem and suffix identification and will provide a foundation for the future investigation of complex nonword reading.

Conclusions

As with other aspects of reading, the careful investigation of cognitive neuropsychological case studies provides real insights into the role of morphological structure during reading. By focusing our investigation on individuals whose word reading is intact, but who have difficulty reading nonwords, we have been able to focus on how morphological structure impacts reading aloud in the absence of familiarity with the whole word. Different patterns emerged in the individuals we tested. All individuals showed morpheme facilitation and stem substitution effects, suggesting that when readers have an intact lexical route and an impaired non-lexical route, embedded morphemes can be used to support the decoding of nonwords. One individual showed these benefits only when the nonword could be fully parsed into a real stem and a real suffix, suggesting a separable morphological parsing mechanism. To be able to account for the richness of language, computational theories of word reading need to broaden to be able to explain how we are able to read morphological complex words and not just morphologically simple words, and cognitive neuropsychological investigations of individuals with acquired dyslexia can help to elucidate the cognitive processes that allow this to happen.

CRediT authorship contribution statement

Elisabeth Beyersmann: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Formal analysis, Visualization, Data curation. **Anne Turney:** Data curation. **Tara Arrow:** Data curation. **Simon Fischer-Baum:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data statement

The data and materials of this manuscript have been made available via the following Open Science Framework repository: https://osf.

io/4cf5j/.

Appendix. Items used in the study

Word Targets

Non-Suffixed	Suffixed
ant	baker
asphalt	treatment
banana	decision
basilisk	servant
custom	stupidity
brush	existence
diamond	fortress
shower	fisherman
success	researcher
flame	freedom
giraffe	hairstyle
guitar	youth
hostel	illness
colleague	artist
chest	power
contact	clearing
control	liar
concert	manager
claw	humanity
wig	musician
puddle	beauty
plate	security
puzzle	settlement
pyramid	winner
soldier	player
stork	position
talent	tracker
tomato	trainer
triumph	training
cigar	wisdom

Nonword Targets

Stem + Suffix	Stem + Non-Suffix	Non-Stem + Suffix	Non-Stem + Non-Suffix
armful	armase	arfful	arfase
treement	treetege	treiment	treitege
legful	legose	ligful	ligose
broomment	broomlude	broosment	brooslude
bedness	bedmose	berness	bermose
flashment	flashnule	flishment	flishnule
bloodful	blooduck	bloudful	blouduck
letterment	letternule	lotterment	lotternule
breadful	breadrel	brealful	brealrel
breaster	breastel	breister	breistel
busness	busnete	bulness	bulnete
roofer	roofel	roifer	roifel
iceful	icenep	ifeful	ifenep
fieldful	fieldane	fierdful	fierdane
filmful	filmose	filtful	filtose
flightment	flightmose	flishtment	flishtmose
hallful	hallept	hollful	hollept
facement	facenure	ficement	ficenure
ghostment	ghostnule	ghistment	ghistnule
stopment	stopnept	stosment	stosnept
woodness	woodnane	woosness	woosnane
henful	henude	honful	honude
dogness	dognule	domness	domnule
biscuitful	biscuitude	bisfuitful	bisfuitful
guyful	guybal	gueful	guebal
headment	headnure	heafment	heafnure
holement	holenept	hilement	hilenept
airment	airnule	aisment	aisnule
mousement	mouserund	moufement	mouferund
milkment	milkrane	molkment	molkrane
moonment	moonhoke	mootment	moothoke
nightness	nightlude	nishtness	nishtlude
nestness	nestnane	nistness	nistnane
parkful	parkure	parmful	parmure

(continued on next page)

(*continued*)

Word Targets			
Non-Suffixed	Suffixed		
horseness	horsenure	horpeness	horpenure
pointment	pointvose	poiltment	poiltvose
wheelment	wheelhoke	wheilment	wheilhoke
lawable	lawnept	lewable	lewnept
juiceness	juicehoke	juileness	juilehoke
sandness	sandlude	santness	santlude
treasureness	treasuremose	treamureness	treamuremose
senseness	senserane	selseness	selserane
trackment	tracklude	trockment	trocklude
stonement	stonelabe	stanement	stanelabe
frontful	frontase	frintful	frintase
dayful	daytege	dauful	dautege
carpetful	carpetrel	carfetful	carfetrel
tablement	tablenept	teblement	teblenept
potful	potaph	pomful	pomaph
tunnelness	tunnelmose	tunfelness	tunfelmose
wallful	wallund	walsful	walsund
worldment	worldnule	worltment	worltnule
windful	windane	wisdful	wisdane
jokement	jokelabe	jubement	jubelabe
wolfful	wolfrel	wolpful	wolprel
wordful	wordane	werdful	werdane
toother	toothel	toither	toithel
timeful	timenul	tiveful	tivenul
tentment	tentlure	tertment	tertlure
trainful	trainege	treinful	treinege

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