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Research report

Prefixes repel stress in reading aloud: Evidence from surface dyslexia☆

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ABSTRACT

This study examined the importance of prefixes as sublexical cues for stress assignment during reading aloud English disyllabic words. In particular, we tested the hypothesis that prefixes repel stress (Rastle & Coltheart, 2000) by investigating the likelihood with which patients with surface dyslexia assign second-syllable stress to prefixed words. Five such patients were presented with three types of disyllabic words for reading aloud: 'regular' prefixed words with weak-strong stress pattern (e.g., remind); 'irregular' prefixed words with strong-weak stress pattern (e.g., reflex); and non-prefixed words with strong-weak stress pattern (e.g., scandal). Results showed that all five patients frequently regularized the strong-weak prefixed words by pronouncing them with second syllable stress. These regularization errors provide strong evidence for the functional role of prefixes in stress assignment during reading. Additional computational simulations using the rule-based algorithm for pronouncing disyllables developed by Rastle and Coltheart (2000) and the CDP++ model of reading aloud (Perry et al., 2010) allowed us to evaluate how these two opponent approaches to reading aloud fare in respect of the patient data.

1. Introduction

Over the past couple of decades, research into the generation of sound from print has begun to move away from a focus on simple monosyllabic words, to consider the special problems posed by multisyllabic words (e.g., Arciuli, Monaghan, & Ševa, 2010; Rastle & Coltheart, 2000). Reading aloud a multisyllabic word requires more than the translation of an orthographic string to its phonological equivalent; it also requires the assignment of stress, which involves the phonetic accentuation of one of the syllables, along with the possible reduction of an unstressed vowel in the word. A clear illustration of these phonetic modulations can be seen in the case of noun/

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verb minimal pairs. For example, the disyllabic English word "suspect" is pronounced/'sVspEkt/[1] when used as a noun (e.g., the usual suspect) and/s@spEkt'/when used as a verb (e.g., to suspect foul play). While the pronunciation of the former is characterised by a first-syllable stress and two phonetically full vowels, the pronunciation of the latter is characterized by a second-syllable stress and the phonetic reduction (schwa) of the vowel in the first syllable.

Several recent studies have investigated the mental processes that underpin stress assignment during reading aloud. These studies have focused on languages characterised by a free-stress system such as English (e.g., Arciuli & Cupples, 2006; 2007; Guion, Clark, Harada, & Wayland, 2003), Italian (see Sulpizio, Burani, & Colombo, 2015 for a review), and Russian (Jouravlev & Lupker, 2014), where stress has neither a fixed position within the word nor is marked by the use of diacritics. These investigations have mainly sought to examine the extent to which stress is determined by word specific stored information (lexical) or statistical-distributional regularities of a given language (sublexical). In respect of this latter dimension, several factors have been identified as potential predictors of stress assignment. These include the distribution of stress patterns in the language (e.g., Arciuli & Cupples, 2006; Colombo, 1992; Kelly & Bock, 1988; Monsell, Doyle, & Haggard, 1989); orthographic sequences, in particular word beginnings and/or endings (e.g., Burani, Paizi, & Sulpizio, 2014; Cappa, Nespor, Ielasi, & Miozzo, 1997; Colombo, 1992; Ševa, Monaghan, & Arciuli, 2009); syllabic weight both at the orthographic (Kelly, 2004; Kelly, Morris, & Verrekia, 1998) and phonological level (Guion et al., 2003); and vowel length (Baker & Smith, 1976; Guion et al., 2003). Of particular importance to the present study is the claim that the morphological structure of a word (i.e., the presence of affixes) also provides important information in determining stress assignment in reading aloud (Rastle & Coltheart, 2000).

Rastle and Coltheart (2000) were among the first researchers to explore the computational processes of stress assignment during the spelling-to-sound translation of a disyllabic stimulus, and to demonstrate how these mechanisms could be implemented within an existing theoretical framework of reading, namely the DRC model (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart & Rastle, 1994; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Rastle & Coltheart, 1999). The DRC model is a computational instantiation of the dual-route theory of reading, the central tenet of which is that the translation of spelling to sound involves two procedures, a lexical procedure whereby item-specific stored knowledge about the relationship between orthography and phonology is retrieved, and a sublexical procedure whereby phonological information is computed from an orthographic string by a set of rules (Coltheart, 1978; Forster & Chambers, 1973; Marshall & Newcombe, 1973). Rastle and Coltheart (2000) suggested that stress information could be stored in the lexical route of the model as a property of item-specific phonological representations, and thus retrieved during the reading aloud of known words. They concentrated instead on the more challenging task of implementing a stress assignment procedure along the sublexical route of the model that could be applied to the reading of disyllabic letter strings without a lexical representation (i.e., unfamiliar words and nonwords).

The rule-based process developed by Rastle and Coltheart (2000) was designed to execute both the mapping between sublexical orthographic and phonological representations (segmental information) and the assignment of stress along with the appropriate vowel reduction (suprasegmental information). Morphological structure plays an important role in the system of rules that Rastle and Coltheart (2000) implemented, particularly in relation to the assignment of stress (for an illustration of the stress rules refer to Figure 2, p. 349 in Rastle & Coltheart, 2000). Specifically, the identification of a prefix (e.g., pre-, de-, dis-. re-, mis-) results in the assignment of second-syllable stress, while the identification of a suffix results in the assignment of first-syllable stress (except in the case of a small group of stress-taking suffixes identified by Fudge (1984) such as –een, –ique, -oo). In the absence of an identifiable affix, first-syllable stress is assigned, which is the dominant stress pattern for disyllables in the English language. Rastle and Coltheart (2000) reported that the algorithm successfully predicted stress assignment on 89.7% of all disyllabic English words present in the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993), and it also predicted the modal stress given to 84% of a large set of disyllabic nonwords read aloud by human subjects. This work thus provides evidence supporting the notion that prefixes can serve as important cues for stress assignment, and more generally, that sublexical cues for assigning stress to disyllables can be expressed within a system of rules relating spelling to sound.

The present study introduces a new approach to ascertaining the sublexical cues to stress assignment. Specifically, we denote prefixed words as 'regular' if they take second-syllable stress (e.g. remind) and 'irregular' if they take first-syllable stress (e.g. reflex). We then test whether patients with acquired surface dyslexia, an acquired disorder of reading in which the reading aloud of irregular words is impaired while the reading aloud of nonwords is spared (Marshall & Newcombe, 1973), are likely to assign second-syllable stress to prefixed irregular words. Typically, these patients produce regularization errors in pronunciation when reading aloud irregular monosyllabic words (e.g., reading *pint* as if it rhymed with *mint*). Thus, while these patients demonstrate an impairment in utilising lexical information during reading, their ability to translate orthography to phonology via sublexical operations appears to be intact. Accordingly, we hypothesized that these patients would commit stress regularisation errors when reading aloud irregularly-stressed disyllabic words (e.g., read 'reflex' with second-syllable stress).

While patients with surface dyslexia have typically been examined in respect of the segmental errors produced during reading aloud, it has long been known that they also produce errors with respect to suprasegmental information (Marshall & Newcombe, 1973). Stress regularization errors in acquired, as well as developmental, surface dyslexia have been

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[1] For consistency reasons we chose to report transcriptions throughout the article using the phonemic vocabulary of the dual-route cascaded model. The glossary of the DRC phonemic vocabulary is provided in Appendix A.

observed in different languages, including English (Marshall & Newcombe, 1973), Italian (e.g., Galante, Tralli, Zuffi, & Avanzi, 2000; Laganaro, Vacheresse, & Frauenfelder, 2002; Miceli & Caramazza, 1993; Paizi, Zoccolotti, & Burani, 2011; Trenta, Benassi, Di Filippo, Pontillo, & Zoccolotti, 2013; Zoccolotti et al., 1999), German (Janssen, 2003), Filipino (Dulay & Hanley, 2015), and Hebrew (Friedmann & Lukov, 2008). In the majority of these studies, stress errors involved overgeneralizations of the most frequent stress pattern of the given language. Surprisingly, however, there has been hardly any work investigating the sublexical knowledge used in stress assignment by patients with surface dyslexia. The only study that examined this issue was carried out by Janssen (2003) in German. In particular, Jannsen (2003) investigated stress error patterns in two patients with surface dyslexia in order to determine whether syllable structure is an important predictor of stress assignment in the German reading system. Inspection of the patients' regularization errors revealed that in German, an open final syllable (i.e., ending with a vowel) leads to a penultimate syllable stress, while a closed final syllable (i.e., ending with a vowel-consonant) preceded by an open syllable leads to a final syllable stress, attesting to the operational role of syllable structure in German stress assignment.

Accordingly, in the present study, we sought to uncover the sublexical cues to stress assignment in the English language by investigating whether patients with acquired surface dyslexia are likely to assign second-syllable stress to prefixed words that are irregularly stressed (e.g. reflex). More specifically, we tested the hypothesis put forward by Rastle and Coltheart (2000) that prefixes repel stress, so that identification of a prefix in a two-syllable letter string leads readers to assign second syllable stress. Patients were given three types of disyllabic words for reading aloud. Two of these types were prefixed words that varied in regularity according to the prefixes-repel-stress rule. The regular prefixed words contained a weak-strong syllable stress pattern and required a second syllable stress (e.g., remind), whereas the irregular prefixed words contained a strong-weak syllable stress pattern and required a first-syllable stress (e.g., reflex). Stress assignment to regular and irregular prefixed words was examined against a third type of control word. These were non-prefixed words that contained a strong-weak stress pattern (e.g., scandal), which is the dominant stress pattern of English disyllabic words in the absence of prefixation. If prefixes repel stress within the sublexical procedure for reading aloud, then we would expect surface dyslexic patients to assign second syllable stress to prefixed words, thus yielding stress errors in the case of ‘irregular’ prefixed words with strong-weak stress.

In addition to reporting data from five surface dyslexic patients on the reading aloud of disyllabic words, we report simulations from the disyllabic algorithm developed by Rastle and Coltheart (2000) and from the CDP++ model developed by Perry, Ziegler, and Zorzi (2010), which are currently the only two publicly available computational implementations of reading aloud that provide both a stress marker and a phonological code for English disyllabic words (see Ans, Carbonnel, & Valdois, 1998, for a polysyllabic model of reading aloud in French). As was mentioned earlier, the disyllabic algorithm developed by Rastle and Coltheart (2000) reflects only the sublexical reading aloud process; the output of this process thus reflects reading in the absence of lexical information (i.e. pure surface dyslexia). Given the nature of the hard-coded rules in the implemented algorithm, hereafter referred to as RC00, our prediction was that the algorithm would assign second-syllable stress to prefixed words and thus, commit stress errors on ‘irregular’ prefixed words with strong-weak stress (e.g., saying reflex as/r@flEks'/). We opted to contrast these simulations with those from the CDP++ model (Perry et al., 2010). CDP++ is a computational implementation of the dual-route theory much like the DRC model (Coltheart et al., 2001), comprising a lexical and a sublexical procedure. However, its sublexical procedure consists of a two-layer associative (TLA) network for mapping graphemes onto phonemes, as opposed to a set of rules. In this model, stress assignment to disyllabic words is coded in a stress buffer that is connected with both the lexical and the sublexical procedures. While the lexical procedure of the model directly activates the stress that is associated with a familiar word's spoken form, the sublexical procedure activates the stress that it learnt to associate with the graphemes of a word. These grapheme to stress associations are learnt during a training phase in the same way as grapheme to phoneme mappings are formed, that is, via a connectionist algorithm based on the statistical distributional regularities of the spelling-to-sound and spelling-to-stress mappings. Surface dyslexia can be simulated in the CDP++ model by lesioning connections within the lexical procedure to varying degrees. The CDP++ model provides an interesting contrast to the RC00 algorithm because prefixes are not explicitly represented in its sublexical pathway. Hence, this model is not expected to be sensitive to associations between prefixes and certain stress patterns. For this reason, we predicted that the CDP++ model may not necessarily assign second-syllable stress to prefixed words, and so it may not commit stress regularisation errors for the prefixed irregular words with strong-weak stress.

The comparison between the RC00 algorithm and the CDP++ model also bears additional theoretical value in respect of how sublexical orthographic knowledge is used to generate phonology at the suprasegmental level during reading in general. Indeed, the comparison of the stress error patterns produced by these models may provide a platform to evaluate the extent to which this generative knowledge is expressed as a set of explicit rules, or as an implicit system of statistical regularities that has been acquired through learning.

2. Case reports

We recruited five cases of acquired surface dyslexia, four female and one male. All were judged to be candidates for surface dyslexia on the basis of (a) impaired irregular word relative to regular word reading and (b) relatively preserved nonword reading. These criteria were assessed through administration of the PALPA 35 and 36 (Psycholinguistic Assessment of Language Processing in Aphasia; Kay, Lesser, & Coltheart, 1992) and the Coltheart and Leahy (1996) reading tests. These assessments were conducted as part of a comprehensive neuropsychological evaluation performed on each individual case. In particular, each case was screened for dementia with the Addenbrooke's Cognitive Examination Revised (ACE-R; Mioshi, Dawson, Mitchell, Arnold, & Hodges, 2006) test battery, while additional tests assessing the different memory and language components were also administered. The administered assessments and the neuropsychological profile of each case are summarized in Table 1. All cases had normal or corrected to normal vision. Below we provide a brief medical history report for each of the five cases, including a short discussion of the patients' cognitive impairments and reading aloud performance at the time in which the present study was conducted.

2.1. *Patient 1*

This patient is a right-handed female, aged 65 at time of testing. She had a four-year history of memory problems with some early history of mild depression, which were subsequently resolved, and no current evidence of a general mood disorder. There was some family history of dementia, with her mother having had vascular dementia. Neurological investigation included a CT undertaken in April 2012, which reported "*asymmetry of the temporal horns of the lateral ventricles with some prominence of the sulci of the temporal lobe on the left. This is in keeping with a degree of left temporal lobe atrophy. No other significant abnormality*." A subsequent MRI undertaken in August 2012 reported "*significant atrophy of the left temporal lobe and to a lesser extent the right. No mass lesion identified*", consistent with primary progressive aphasia. The patient undertook a degree in natural sciences and after graduation worked as a teacher, married, and raised a family.

Upon presentation, general cognitive testing indicated an impaired profile (ACE-R score 50/100) somewhat complicated by clear expressive and receptive aphasia – although some episodic memory impairment was present. Expressive aphasic presentation was evident on the basis of verbal fluency impairment and severe naming problems, though word repetition testing and auditory verbal short-term memory were normal (see Table 1). Severe semantic memory impairment was also present as assessed by the Pyramids and Palm Trees test (PPT, Howard & Patterson, 1992), where she obtained a score of 36 out of 52. The presence of semantic errors in naming and impaired comprehension, along with anterior temporal lobe atrophy (accentuated in the left hemisphere) are considered consistent with semantic dementia (Gorno-Tempini et al., 2011). Critically, Patient's 1 reading assessment (PALPA 35, 36, and Coltheart & Leahy tests combined) exhibited the distinctive pattern of surface dyslexia, characterized by impaired irregular word reading (40% correct) in the presence of relatively spared regular word and nonword reading (96.7% and 94.6% correct, respectively). Notably, the vast majority of reading errors on irregular words involved spelling-to-sound regularizations (88.9%). Such errors reflect Patient's 1 reliance on the sublexical reading procedure. Examples of regularization errors included/jQJt/for the word 'yacht',/b6l/for the word 'bowl', and/J4@/for the word 'choir'.

2.2. *Patient 2*

This patient is a right-handed female, aged 63 at time of testing. She had a four-year history of memory and language problems, with some consequential anxiety but no other evidence of generalized mood disorder. Osteo-arthritis in the knees was her only other physical complaint. There was also a history of dementia in the family, with her mother having developed Alzheimer's Disease (AD). Neurological investigation included a CT undertaken in March 2012, which reported "*mild features of general atrophy with widening of the Sylvian fissure and associate bilateral temporal lobe convexity. No evidence of any ischaemic change or mass lesion identified*", with a diagnosis of fronto-temporal dementia with primary progressive aphasia of the non-fluent subtype. The patient had been a homemaker throughout her life, leaving school at 16 to work for a brief period in retail, and is bilingual in Welsh and English.

Upon presentation, general cognitive testing indicated a dementia cognitive profile (ACE-R score 25/100) with episodic memory impairment and constructional apraxia as specified by her performance in the Rey-Osterrieth Complex Figure test (ROCF; Osterrieth, 1944). Expressive and receptive aphasic presentation was evident. Speech production was non-fluent at presentation, with severe auditory verbal short memory impairment, and word repetition, fluency and word naming problems (see Table 1). Mild semantic memory impairment was also present (PPT score 46/52). Patient's 2 reading assessment (PALPA 35, 36, and Coltheart & Leahy tests combined) revealed a surface dyslexia profile. Specifically, Patient's 2 regular word and nonword reading was highly accurate (83.3% and 85.4% correct, respectively), whereas irregular word reading was considerably impaired (48.3% correct). Errors to irregular words included 64.3% of spelling-to-sound regularizations, indicative of a reliance on the sublexical reading procedure. Examples of such regularizations included/pInt/for the word 'pint',/s6l/for the word 'soul',/'2rQn/and for the word 'iron'.

2.3. *Patient 3*

This patient is a right-handed male, aged 61 at time of testing. He had a three-year history of memory problems with some history of anxiety (treated with medication), but no generalized mood disorder and no family history of dementia. Neurological investigation included a CT undertaken in March 2012, which reported "*mild widening of the subarachnoid spaces in relation to the temporal lobes with widening of the Sylvian fissures and sulci. No evidence of focal ischaemic change*", with a diagnosis of AD. The patient had left school at 18 and worked as an insulation engineer throughout his professional life, marrying, and having children.

Upon presentation, general cognitive testing indicated a dementia cognitive profile (ACE-R score 37/100) with episodic memory impairment and constructional apraxia as specified by the patient's ROCF test performance. No expressive aphasic presentation was evident on the basis of only mild naming problems and normal word repetition testing, though verbal fluency was severely impaired, as was auditory verbal short-term memory (see Table 1); semantic memory impairment was also present (PPT score 37/52). Patient's 3 reading assessment (PALPA 35, 36, and Coltheart & Leahy tests combined) revealed a surface dyslexia profile. Specifically, while Patient's 3 regular word reading was virtually perfect (96.7% accurate) and his nonword reading highly accurate (83.3%

Table 1 – Neuropsychological assessment of patients.

	Patient				
	1	2	3	4	5
General cognition					
Total ACE-R score	50/100	25/100	37/100	32/100	62/100
Diagnosis	PPA – SD	PPA – NFPA	AD	AD	FTD
Memory					
Verbal/Nonverbal STM					
Digit Span Forward/Backward (WMS-III)	6 *vs* 4	2 *vs* 0	4 *vs* 1	5 *vs* 2	4 *vs* 3
Spatial span (WMS-III)	6 *vs* 5	2 *vs* 0	4 *vs* 2	4 *vs* 3	3 *vs* 3
Verbal/Nonverbal LTM					
HVLT-R	3-3-4	–	3-5-6	–	3-3-4
ROCF copy	36/36	apraxia	apraxia	apraxia	32/36
ROCF delay	15/36	–	–	–	2/36
Verbal/Nonverbal Recognition					
Words (Warrington)	27/50	28/50	28/50	40/50	26/50
Faces (Warrington)	38/50	33/50	31/50	36/50	28/50
Language					
Verbal fluency					
Semantic					
Animals (ACE-R)	14	2	3	5	7
Letter					
FAS	13	4	3	0	16
Comprehension					
PPT	36/52	46/52	37/52	44/52	46/52
Naming					
Picture (PALPA 40)	11/40	5/40	34/40	38/40	32/40
Repetition					
Repetition (PALPA 9)					
Words	40/40	8/20	40/40	40/40	39/40
Nonwords	40/40	3/20	39/40	40/40	37/40
Reading					
NART	6/50	6/50	15/50	15/50	22/50
Regularity (PALPA 35)					
Regular	29/30	25/30	29/30	28/30	29/30
Irregular (regularization errors)	12/30 (83.3%)	19/30 (63.6%)	25/30 (40.0%)	24/30 (50.0%)	26/30 (100%)
Nonwords (PALPA 36)	23/24	21/24	20/24	21/24	21/24
Coltheart & Leahy					
Regular	29/30	25/30	29/30	29/30	29/30
Irregular (regularization errors)	12/30 (94.4%)	10/30 (65.0%)	19/30 (54.6%)	23/30 (57.1%)	20/30 (80.0%)
NWs	28/30	25/30	26/30	28/30	28/30

Note. **Diagnoses:** PPA = Primary Progressive Aphasia; SD = Semantic Dementia; NFPA = Non-Fluent Progressive Aphasia; AD = Alzheimer's Disease; FTD = Fronto-Temporal Dementia; apraxia = constructional apraxia. **Assessments:** ACE-R = Addenbrooke's Cognitive Examination Revised (Mioshi, Dawson, Arnold, & Hodges, 2006); Coltheart & Leahy tests, (Coltheart & Leahy, 1996); FAS letter fluency test (Spreen & Strauss, 1998); HVLT-R = Hopkins Verbal Learning Test – Revised (Benedict, Schretlen, Groninger, & Brandt, 1998); NART = National Adult Reading Test (Nelson & Wilson, 1991); PALPA = Psycholinguistic Assessment of Language Processing in Aphasia (Kay et al., 1992); PPT = Pyramids & Palm Trees Test (Howard & Patterson, 1992); ROCF = Rey-Osterrieth Complex Figure test (Osterrieth, 1944); Warrington Words and Faces tests (Warrington, 1984); WMS-III = Wechsler Memory Scale-III (Psychological Corporation, 1997).

correct), this patient's irregular word reading was relatively impaired (73.3% correct). Patient 3 regularized the spelling-to-sound pronunciation of 47.3% of all irregular words, reflecting a reliance on the sublexical reading procedure. Examples of such regularizations included/tQm/for the word ‘tomb’,/kw1/ for the word ‘quay’, and/su/for the word ‘sew’.

2.4. *Patient 4*

This patient is a right-handed female, aged 65 at time of testing. She had a three-year history of memory problems, with no evidence of generalized mood disorder or family history of dementia. Neurological investigation included a CT undertaken in June 2013, which reported “*a disproportionate level of atrophy affecting the frontal lobes bilaterally. Additionally marked prominence of widening of the Sylvian fissure associated with temporal lobe atrophy. No evidence of focal ischaemic change or mass lesion identified*”, with a diagnosis of dementia of the Alzheimer's type. The patient left school at 16 to work in domestic employment at a children's home and raise a family.

Upon presentation, general cognitive testing indicated a dementia cognitive profile (ACE-R score 32/100) with episodic memory impairment and constructional apraxia as specified by the patient's ROCF test performance. No expressive aphasic presentation was evident on the basis of naming and word repetition testing, though verbal fluency was severely impaired, as was auditory verbal short-term memory (see

Table 1); mild semantic memory impairment was also present (PPT score 44/52). Patient's 4 reading assessment (PALPA 35, 36, and Coltheart & Leahy tests combined) revealed a surface dyslexia profile. Specifically, while Patient's 4 regular word reading was virtually perfect (95% accurate) and nonword reading highly accurate (90.4% correct), this patient's irregular word reading was relatively impaired (78.3% correct). Patient 4 regularized the spelling-to-sound pronunciation of 53.6% of all irregular words, reflecting a reliance on the sublexical reading procedure. Examples of such regularizations included/rut2n'/ for the word ‘routine’,/kw1/for the word ‘quay’, and/'Izl}nd/for the word ‘island’.

2.5. *Patient 5*

This patient is a right-handed female, aged 69 at time of testing. She had a three-year history of memory problems, but no evidence of any mood disorder and no family history of dementia. She also receives medication for hypothyroidism. Neurological investigation included a CT conducted in December 2013, which reported *“mild generalized atrophy, prominent around frontal operculum bilaterally and including antero-temporal lobes. No evidence of ischaemic change*”, with a diagnosis of fronto-temporal dementia. The patient left school at 16 to work as a shop assistant and subsequently as a warehouse manager, marrying, and having children.

Upon presentation, general cognitive testing indicated a dementia cognitive profile (ACE-R score 62/100) with episodic memory impairment. Some expressive aphasic presentation was evident on the basis of moderate naming problems and impaired verbal fluency – but normal word repetition testing and mild impairments of auditory verbal short-term memory (see Table 1); mild semantic memory impairment was also present (PPT score 46/52). Patient's 5 reading assessment (PALPA 35, 36, and Coltheart & Leahy tests combined) revealed a surface dyslexia profile. Specifically, while Patient's 4 regular word reading was virtually perfect (96.7% accurate) and nonword reading highly accurate (90% correct), this patient's irregular word reading was relatively impaired (76.7% correct). Notably, Patient's 5 errors on irregular words included a striking 90.4% of spelling-to-sound regularizations. The nature of these errors reflect the patient's reliance on the sublexical reading procedure. Examples of such regularizations included/g9g/for the word ‘gauge’,/IndIkt'/for the word ‘indict, and/'k5l@nEl/for the word ‘colonel’.

3. Method

3.1. *Stimuli*

One hundred and fifty disyllabic English words were selected for inclusion in three conditions. The ‘Prefix W–S’ condition comprised 50 words that had a prefix and were characterised by a weak-strong syllable stress pattern; that is, their correct pronunciation required second syllable stress (e.g., remind, subtract). These items were considered ‘regular’ according to the ‘prefixes-repel-stress’ rule. The ‘Prefix S–W’ condition comprised 50 words that also had a prefix but were characterised by a strong-weak syllable stress pattern; that is, their correct pronunciation required first syllable stress (e.g., reflex, subway). These items were considered ‘irregular’ according to the ‘prefixes-repel-stress’ rule. Finally, the ‘NoPrefix S–W’ condition comprised 50 words that had no prefix and were characterised by a strong-weak syllable stress pattern, which is the dominant stress pattern of English disyllabic words in the absence of prefixation. The correct pronunciation of these control words required first syllable stress (e.g., scandal, volume). Note that prefixation was defined on a purely orthographic basis (see Rastle & Davis, 2008 for relevant discussion). A word was considered as prefixed if it began with a letter sequence that could form an identifiable English prefix, and was followed by either an existing stem (e.g., remove) or by a potential stem (e.g., discreet). The two prefixed conditions (Prefix W–S and Prefix S–W) consisted of the same set of prefixes, which appeared equally frequently in each of these conditions and were predominantly associated with second syllable stress in disyllabic English words. The presence of an embedded word was also controlled, so that half of the items in each of the three conditions contained an embedded ‘stem’ (e.g., re*move*, in*put*, cli*mate*, respectively), whereas the other half did not (e.g., discreet, prospect, minute, respectively).

Words in the three conditions were group-wise matched as closely as possible on CELEX word frequency (Baayen, Piepenbrock, & Gulikers, 1995), word length in letters, orthographic neighbourhood size (Coltheart's N), bigram type frequency (values extracted from the N-Watch database, Davis, 2005) and age of acquisition (AoA, Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012). The mean values of these variables across the experimental conditions are reported in Table 2. Stimuli and patient responses are listed in Appendix B. Patients' responses were transcribed using the same phonemic vocabulary adopted by both the RC00 algorithm and the CDP++ model.

3.2. *Procedure*

All five patients were presented with the 150 stimuli in a random order and were asked to read them aloud within a single testing session.

4. Results

4.1. *Patient data*

For each patient, the percentage of stimuli given second-syllable stress was calculated in each condition (see Table 3). This percentage was based on all intelligible disyllabic responses. Critically, responses that comprised second-syllable stress in the Prefix S–W and NoPrefix S–W conditions were stress errors (e.g.,/Ins2t'/for insight;/bISQp'/ for bishop, respectively). Further examination of these stress errors sought to assess whether they could be deemed *pure* stress errors. Pure stress errors were defined as responses that contained an erroneous stress assignment but the correct phonemic pronunciation of the word.

Table 2 – Stimulus characteristics (means and standard deviations) for words in each condition.

	Word frequency	Word length	Coltheart's N	AoA	Bigram frequency
Prefix W–S (e.g., remind)	Mean: 25.77 SD: 28.72	Mean: 6.46 SD: .89	Mean: .54 SD: .71	Mean: 9.26 SD: 2.16	Mean: 43.89 SD: 26.97
Prefix S–W (e.g., reflex)	Mean: 23.79 SD: 42.95	Mean: 6.30 SD: .91	Mean: .76 SD: 1.32	Mean: 10.22 SD: 2.42	Mean: 42.64 SD: 25.29
NoPrefix S–W (e.g., scandal)	Mean: 25.10 SD: 28.99	Mean: 6.72 SD: .78	Mean: .28 SD: .50	Mean: 7.52 SD: 2.24	Mean: 48.93 SD: 19.87

Pronunciations that were slightly altered as a result of the erroneous stress assignment (e.g., reducing to schwa the initial vowel in ‘agate’), or that involved spelling-to-sound regularizations (e.g.,/dIpQt'/for the word ‘depot’), were also classified as pure stress errors. Non-pure stress errors involved incorrect pronunciations in addition to stress displacement (e.g.,/pVt5t'/for the word ‘input’). As shown in Table 3, the vast majority of incorrect second-syllable stress assignments to Prefix S–W and NoPrefix S–W words fall into the pure stress error category. This pattern is consistent across all patients.

Patients' responses are reported in Appendix B. It is noteworthy that beyond stress assignment errors, all patients produced a number of spelling-to-sound regularization errors, which are characteristic of surface dyslexia. In order to quantify the incidence of spelling-to-sound regularisations, we identified words in our stimulus set that both RC00 and the sub-lexical pathway of the CDP++ model produced incorrectly. There were 20 such items (or, 100 opportunities to observe spelling-to-sound regularisations). Patients produced regularisations in 40% of these cases while an additional 6% of the responses were either missing or otherwise incorrect. The words that were systematically regularized by the majority of patients (3 and above) were the following: depot (/dIpQt'/), climate (/'kl2m1t/), diamond (/'d2mQnd/), minute (/mInut'/), surface (/'s3f1s/), message (/'mEs1_/), fountain (/'f6nt1n/), mountain (/'m6nt1n/), and input (/'InpVt/). These regularisations in pronunciation provide further evidence of the patients' surface dyslexia.

Logistic regression analyses were carried out for each patient individually. These analyses investigated the probability of second-syllable stress occurring (a binary variable) as a function of condition (3 levels) and the presence of an embedded word (another binary variable). Although our stimuli were closely matched on the psycholinguistic characteristics presented in Table 2, we included these continuous variables as covariates in the analysis of each patient to ensure that any effects of our factors of interest were not driven by small differences in these variables across the three conditions. However, for ease of exposition, we report only those results relevant to our factors of interest, together with those covariates that contributed significantly to the assignment of second-syllable stress. To reiterate our main hypothesis, if prefixes repel stress, we would expect patients to depart from the typical strong-weak stress pattern of English disyllables and assign second-syllable stress to prefixed words. Specifically, relative to the control NoPrefix S–W words, we hypothesized that patients would be more likely to assign second-syllable stress to both regular Prefix W–S words and irregular Prefix S–W words. Second-syllable stress assignment to the latter words would denote stress regularisation errors.

Table 3 – Percentage of second syllable stress assignment for each patient in each condition.

Patient	% 2nd-syllable stress		
	Prefix W–S ‘regular’	Prefix S–W ‘irregular’	NoPrefix S–W
1	98.0	88.0 (84.0)	46.0 (42.0)
2	98.0	91.5 (89.3)	22.9 (22.9)
3	87.8	42.9 (36.7)	2.0 (2.0)
4	97.8	62.5 (47.9)	4.3 (4.3)
5	91.5	69.4 (67.3)	6.8 (6.8)

Note. Percentage of second syllable stress assignments for Prefix S–W and NoPrefix S–W words denote stress errors (pure stress errors are shown in parentheses).

Results revealed a significant influence of condition on the production of second-syllable stress for all patients. The Wald test statistics for the main effect of condition and the follow-up comparisons for each patient are reported in Table 4. All patients were more likely to assign second-syllable stress to Prefix W–S words, relative to NoPrefix S–W words, with an odds ratio ranging from 139.5 (for Patient 5) to 774.0 (for Patient 4). More importantly, all patients were more likely to incorrectly assign second-syllable stress to Prefix S–W words compared with NoPrefix S–W words, with an odds ratio ranging from 16.8 (for Patient 3) to 70.2 (for Patient 2). None of the patients revealed an effect of embedded words on the probability of assigning second-syllable stress. The Wald test statistics for the main effect of embedded word for each patient are also reported in Table 4. The covariates did not reveal significant effects on second-syllable stress assignment patients 2, 4, and 5 (all *p* values >.05). For Patient 1, the effect of orthographic length was significant [W(1) = 10.61, *p* = .001], indicating that longer words were 3.2 times more likely to receive second-syllable stress than shorter words.[2] For Patient 3, the effects of age of acquisition and orthographic length were significant [W(1) = 4.32, *p* = .038, and W(1) = 4.32, *p* = .038,

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[2] Because of Patient 1's severe semantic memory impairment (see Table 1) we also examined the potential influence of word imageability on this patient's stress error data. In a separate regression analysis we included word imageability ratings (Schock, Cortese, & Khanna, 2012) as an additional covariate and found no imageability effect on the probability of producing second-syllable stress.

Table 4 – Wald test statistics for the main effect of condition and pairwise comparisons, and the main effect of embedded word, for each patient. Odds ratio (OR) is reported where appropriate.

			Patient				
			1	2	3	4	5
Condition			W(2) = 23.25 $p < .001$	W(2) = 32.09 $p < .001$	W(2) = 36.06 $p < .001$	W(2) = 28.76 $p < .001$	W(2) = 35.14 $p < .001$
Prefix W–S ‘regular’	**versus**	**NoPrefix S–W**	W(1) = 16.95 $p < .001$ OR: 146.9	W(1) = 22.49 $p < .001$ OR: 356.1	W(1) = 26.31 $p < .001$ OR: 330.2	W(1) = 27.76 $p < .001$ OR: 774.0	W(1) = 34.97 $p < .001$ OR: 139.5
Prefix S–W ‘irregular’			W(1) = 15.92 $p < .001$ OR: 23.6	W(1) = 22.21 $p < .001$ OR: 70.2	W(1) = 6.64 $p = .01$ OR: 16.8	W(1) = 13.53 $p < .001$ OR: 22.7	W(1) = 19.27 $p < .001$ OR: 28.3
Embedded Word			W(1) < .01 $p = .971$	W(1) = .56 $p = .456$	W(1) < .01 $p = .944$	W(1) = .20 $p = .652$	W(1) = .07 $p = .793$

respectively], indicating that words that were acquired later in life were 1.3 times more likely to receive second-syllable stress, and longer words were less likely to be stressed on the second syllable than shorter words.

4.2. *Simulations*

Simulations were run using the RC00 algorithm (Rastle & Coltheart, 2000) and the executable version of the CDP++ model (Perry et al., 2010). None of the patients showed totally impaired irregular word reading in the presence of totally unimpaired nonword and regular word reading. However, our simulations represent the case of pure surface dyslexia. While we acknowledge that this is a simplification, the RC00 algorithm only expresses a set of hypotheses about the sublexical rules relating spelling to sound and spelling to stress for disyllabic letter strings. Hence, this model can only simulate pure surface dyslexia. In order to simulate pure surface dyslexia with the CDP++ model, the lexical route was deactivated. In what follows, we describe the sublexical rules used by the RC00 algorithm and the sublexical procedure of the CDP++ model for the pronunciation and stress marking of English disyllabic words.

4.2.1. *RC00 algorithm*

The RC00 algorithm (Rastle & Coltheart, 2000) is an implementation of a rule-based sublexical pathway that translates printed disyllables to sound and applies a stress marker. The RC00 algorithm calls on the grapheme-to-phoneme translation rules used by the DRC model and in addition, it identifies orthographic strings corresponding to prefixes and suffixes to determine stress placement. The algorithm begins by searching a letter string for the presence of an existing prefix in the English language (e.g., pre-, de-, dis-. re-, mis-). A prefix is identified on a purely orthographic basis and only if it is followed by an orthographically existing bigram in the first two positions of any monosyllabic English word. Once a prefix is identified, its pronunciation is obtained from the affix store; the remaining part of the word is translated via the grapheme-to-phoneme rules used by the DRC model (Coltheart et al., 2001). The pronunciation of the word is then assembled and the prefix is given non-stress and reduced vowel schwa if appropriate. In the absence of a prefix, the algorithm uses a similar procedure to search for the presence of a suffix at the end of the string. The presence of certain suffixes (i.e. the suffix -y or a suffix that begins with -e) lengthens the first phonological vowel of the string, and the suffix is given non-stress unless it belongs to a group of stress-taking suffixes identified by Fudge (1984; e.g., –een, –ique, -oo), in which case it is given stress. All non-suffixed letter strings are translated into a string of phonemes using the DRC grapheme-to-phoneme rules and are given first-syllable stress.

4.2.2. *CDP++ model*

The CDP++ model is a dual-pathway model of reading aloud comprising lexical and sublexical processes for mapping print-to-sound. The CDP++ model is a full processing model that produces a pronunciation, stress marker, and reaction time. It is built on its direct precursor, the CDP+ model (Perry, Ziegler & Zorzi, 2007), a successful model of reading aloud monosyllabic words. The CDP++ model is very similar to the CDP+ model except that it includes more letter and phoneme slots to accommodate longer words, a different input coding scheme to accommodate disyllables, it introduces the schwa phoneme to deal with vowel reduction and stress nodes to represent the position of stress, and it uses a larger training corpus and lexicon. As in the CDP+ model, the core component of the sublexical procedure of the CDP++ model is the TLA network of phonological assembly. The TLA network contains grapheme nodes that are linked to phoneme nodes via weighted connections that represent the most reliable mappings between orthography and phonology. These mappings are learnt via a connectionist algorithm during training, where the model is exposed to a large word corpus. The TLA network of the CDP++ model also contains two separate sublexical stress nodes for first and second-syllable stress, respectively. The sublexical stress nodes are fully connected to the sublexical grapheme nodes. During training, the model learns grapheme to stress relationships directly, in the same way and under the same parameters as it learns grapheme to phoneme relationships. Activation from the sublexical stress nodes is sent to two stress output nodes that are placed at the level of the phonological output buffer via an excitation parameter. In order to avoid a first-syllable stress bias in the phoneme output buffer, sublexical stress activation begins to activate the stress output nodes only after the last letter of the word is processed by the model's graphemic parser. Finally, a lateral inhibition parameter at the stress output level, allows activation from one stress output node to laterally inhibit the other. The stress output nodes also pool information from the lexical procedure of the model, where lexically defined stress information is sent via excitation and inhibition parameters from the phonological lexicon to the phonological output buffer. In the present simulation of pure surface dyslexia, the lexical procedure of the CDP++ model was completely switched off, so that it would not contribute at all to word reading aloud.

4.3. *Simulation data*

Table 5 below reports the percentages of second-syllable stress assigned by the RC00 algorithm and the CDP++ model across all conditions. As with the patient data above, stress assignments were calculated only for disyllabic responses. The responses produced by the algorithm and the CDP++ model are reported in Appendix B, where the excluded responses are also indicated. Logistic regression analyses were carried out separately for the RC00 algorithm and the CDP++ model, in the same way they were performed for the patient data.

4.3.1. *RC00 algorithm*

The simulation results revealed a significant influence of condition on the assignment of second-syllable stress [$W(2) = 43.43$, $p < .001$]. The RC00 algorithm was 160.9 times more likely to assign second-syllable stress to regular Prefix W–S words than NoPrefix S–W words [$W(1) = 35.14$, $p < .001$]. More importantly, the RC00 was 153.8 times more likely to stress the second syllable of the irregular Prefix S–W words, compared with the NoPrefix S–W words [$W(1) = 30.83$, $p < .001$]. There was no effect of embedded words on the probability of assigning second syllable stress [$W(1) = .30$, $p = .584$]. None of the covariates revealed any significant effects on second-syllable stress assignment (all p values >.05).

4.3.2. *CDP++ model*

The simulation results revealed a significant influence of condition on the assignment of second-syllable stress [$W(2) = 28.19$, $p < .001$]. The CDP++ model was 182.8 times more likely to assign second-syllable stress to regular Prefix W–S words than NoPrefix S–W words [$W(1) = 22.26$, $p < .001$]. Importantly, the CDP++ model was 27.6 times more likely to stress the second syllable of the irregular Prefix S–W words, compared with the NoPrefix S–W words [$W(1) = 9.19$, $p = .002$]. There was no effect of embedded words on the probability of assigning second syllable stress [$W(1) = .68$, $p = .410$]. The effect of age of acquisition was nearly significant [$W(1) = 3.83$, $p = .05$], indicating that words with a higher age of acquisition were 1.3 times more likely to be assigned second-syllable stress. All other covariates revealed no significant effects on second-syllable stress assignment (all p values >.05).

Table 5 – Percentage of second-syllable stress assignment across the three conditions for the RC00 algorithm and CDP++ model.

	% 2nd-syllable stress		
	Prefix W–S 'regular'	Prefix S–W 'irregular'	NoPrefix S–W
RC00 algorithm	94.0	93.9 (93.9)	8.0 (8.0)
CDP++ model	81.2	50.0 (48.9)	2.1 (2.1)

Note. Percentage of second syllable stress assignments for Prefix S–W and NoPrefix S–W words denote stress errors (pure stress errors are shown in parentheses).

5. Discussion

The vast majority of work on the sublexical knowledge between orthography and phonology has focused on the segmental level – that is, the relationship between graphemes and phonemes (e.g., Andrews & Scarratt, 1998; Pritchard, Coltheart, Palethorpe, & Castles, 2012). The present study is concerned with the relationship between orthography and phonology at the suprasegmental level – specifically, the assignment of appropriate stress patterns to letter strings with more than one syllable. Multiple sublexical cues to stress have been put forward (e.g., vowel length, orthographic weight, morphological structure); in this work, we focused on the role of morphological structure on stress assignment. In particular, we tested the hypothesis that prefixes repel stress (Rastle & Coltheart, 2000) by examining whether patients with acquired surface dyslexia are likely to assign second-syllable stress to prefixed words with an irregular stress pattern (e.g. reflex). We reasoned that if prefixes repel stress along the sublexical reading process, these patients should be more likely to incorrectly assign second-syllable stress to these items, leading them to commit stress regularisation errors.

Results confirmed our prediction. All patients assigned significantly more second syllable stress to prefixed words relative to non-prefixed words with a strong-weak stress pattern (e.g., scandal). All patients correctly assigned second-syllable stress to the vast majority of regular weak-strong prefixed words. Critically, all patients committed regularization errors by incorrectly assigning second-syllable stress to irregular prefixed words with a strong-weak stress pattern (e.g., reflex) compared with non-prefixed words that shared the same stress pattern (e.g. scandal). This result was observed consistently across all five patients and interestingly, the likelihood of producing stress regularization errors varied across patients, reflecting their varying levels of surface dyslexia. For example, Patients 1 and 2 produced the greatest number of regularization errors (88.0% and 91.5%, respectively) and as reflected by their very low scores in their irregular reading assessments (PALPA 35, Coltheart & Leahy, 1996; see Table 1), these patients seem to rely almost exclusively on their sublexical procedures for the orthography to phonology mapping.

It is important to note that besides the patients' regularization errors on irregular strong-weak prefixed words, we also observed some stress errors in the other two types of words. In particular, patients incorrectly assigned second-syllable stress to some non-prefixed strong-weak words (Patients 1 and 2 especially), and their performance to regular prefixed weak-strong words was not perfect, as some of these words were assigned first-syllable stress. Thus, it could be argued that the patients' stress errors may have resulted from a cognitive impairment other than or additional to surface dyslexia, such as a deficit in the phonological output buffer (Patient 2 exhibits very poor word and nonword repetition, for example). However, if that were the case we would not expect to observe the systematic pattern of stress regularizations for irregular strong-weak prefixed items that all patients clearly demonstrated. If anything, we would expect more stress errors for prefixed words with a weak-strong stress pattern, which is by far more infrequent in the English language than the strong-weak stress pattern in English disyllabic words. Instead, the vast majority of the prefixed words with a weak-strong stress pattern were correctly assigned second-syllable stress by all patients. The great preponderance of stress errors on the irregular prefixed words, systematically shown by all patients, provides support for the idea that the presence of a prefix prompted patients to assign second-syllable stress, regularizing thus, stress assignment to these items. Overall, these findings confirm the hypothesis that prefixes repel stress in reading aloud disyllabic words and, together with Rastle and Coltheart's (2000) work, establish the functional value of prefixes as sublexical cues to stress assignment in reading.

Results from the computational simulations revealed that the RC00 algorithm was more likely to assign second-syllable stress to prefixed words than to non-prefixed words, producing a considerable number of stress errors for irregular strong-weak prefixed words. This pattern was entirely expected, of course, since the RC00 algorithm includes a rule that assigns second syllable stress to disyllables with prefixes. One limitation of this algorithm is that it is not a fully implemented model (i.e. it is not integrated with the lexical route of the DRC model; Coltheart et al., 2001). For this reason, it is only able to simulate pure surface dyslexia – the total impairment of the lexical procedure in the presence of full functioning of the sublexical procedure. Thus, while this simulation has been able to approximate the number of regularization errors made by the most impaired patients, Patients 1 and 2, the model did not capture accurately the performance in of patients with milder cases of surface dyslexia could also be captured. We are also mindful that the most impaired patients additionally made a substantial number of stress errors on non-prefixed words. This was not the case for the RC00 algorithm. These errors likely reflect additional sublexical cues to stress that are not represented in the RC00 algorithm.

Simulation results from the CDP++ model (Perry et al., 2010) were rather surprising. In a simulation of pure surface dyslexia (with the lexical route of the model completely switched off), this model also produced a large number of stress errors for the irregular strong-weak prefixed words (50%) compared with the non-prefixed strong-weak words. This performance approximated the performance of Patients 3 and 4. These findings are rather surprising because unlike the RC00 algorithm, prefixes are not explicitly represented in the CDP++ model. The sublexical procedure of the CDP++ model consists of a TLA network, which maps graphemes to phonemes and graphemes to stress nodes. In this model, grapheme-to-phoneme and grapheme-to-stress relations are implicitly learned through their statistical distribution in the lexicon, rather than being represented as a hard-wired set of rules as in the RC00 algorithm. Nevertheless, the results from the current simulations suggest that the TLA network forms some association between prefixes and second-syllable stress. The CDP++ model appeared to do more poorly on correctly assigning second-syllable stress to regular weak-strong prefixed words than did most of the patients, but again, approximated the results from Patient 3 on this dimension (81.2%).

While our simulations with the CDP++ model represented the case of pure surface dyslexia, it is important to note that this model is well suited to simulating varying levels of severity in surface dyslexia. This is achieved by gradually lesioning connections within the lexical procedure to varying degrees, as opposed to turning this procedure off entirely. Because our patients clearly exhibit surface dyslexia of varying levels of severity, our original intention was to conduct these more graded simulations. However, the results from the current simulation, which assumed no contribution from the lexical route, removed the rationale for conducting this additional modelling work. Even with the lexical route completely turned off, the model yielded a percentage of stress errors in the irregular S–W prefix condition that was lower than four of the five patients. It is difficult to conceive how more subtle lesions within the lexical pathway could increase the percentage of stress errors in this condition to simulate the more severe cases of surface dyslexia (e.g. Patients 1 and 2). The CDP++ model also displays some problems in the actual responses that it produces, which are unlike those of the patients in various ways. For example, in contrast to the patients, the CDP++ model produced monosyllabic responses for a number of items (e.g., injure/In_’/; pigeon/’p2_/; borough/’b9r/). It also produced impossible responses in which the schwa vowel was stressed (e.g., return/rEt@n’/), or both vowels were reduced to schwa (e.g., conclude/k@@dd’/). The fact that the model produces responses that are atypical of human responses has already been highlighted in the monosyllabic domain (Pritchard et al., 2012). Our work demonstrates that these generalisation problems are also apparent in the disyllabic domain.

In conclusion, we have presented a new approach to investigating sublexical cues to stress assignment in reading aloud. By investigating stress regularizations produced by five patients with surface dyslexia we have shown that the morphological structure of a stimulus (in particular, prefixation) provides important information as to its likely stress pattern. Further, while the simulations do not conclusively favour one theoretical approach to reading aloud over the other, they do highlight challenges for each of the models as they are developed further.

Appendix A. The phonemic vocabulary used in the transcription of the patients' and models' responses. Each symbol's associated phoneme is marked in bold in examples of English words. Adapted from Rastle and Coltheart (1999).

Symbol	Example	Symbol	Example	Symbol	Example	Symbol	Example
1	b**ay**	J	**ch**eap	h	**h**ad	v	**v**at
2	b**uy**	N	ba**ng**	i	b**ea**n	w	**wh**y
3	b**ur**n	Q	p**o**t	j	**y**ank	z	**z**ap
4	b**oy**	S	**sh**eep	k	**c**ad	#	b**ar**n
5	n**o**	T	**th**in	l	**l**ad	{	p**a**t
6	br**ow**	U	p**u**t	m	**m**ad	_	**j**eep
7	p**eer**	V	p**u**tt	n	**n**at	@ (schwa)	inf**a**nt
8	p**air**	Z	mea**s**ure	p	**p**at		
9	p**oor**	b	**b**ad	r	**r**at		
D	**th**en	d	**d**ad	s	**s**ap		
E	p**e**t	f	**f**at	t	**t**ack		
I	p**i**t	g	**g**ame	u	b**oo**n		

Appendix B. Stimuli and patients' and models' reading aloud responses.

Stimulus	Condition	Patient					Model	
		1	2	3	4	5	RC00	CDP++
adjust	Prefix W–S	@d_Vst'	@d_Vst'	@d_Vst'	@d_Vst'	@d_Vst'	@d_Vst'	@_Vst'
alive	Prefix W–S	@l2v'	@l2v'	@l2v'	@l2v'	NR*	@l2v'	@lIv'
amuse	Prefix W–S	@mjuz'	@mus'	{mjuz'	@mjuz'	@mjuz'	@mjuz'	@mjus'
arise	Prefix W–S	@r2z'	@r2s'	@r2z'	@r2s'	@r2s'	@r2z'	#r2z'
confirm	Prefix W–S	kQnf3m'	kQnf3m'	kQnf3m'	kQnf3m'	kQnf3m'	k@nf3m'	k@nf3m'
contempt	Prefix W–S	kQntEmpt'	kQntEmpt'	'kQntEmpt	kQmEnt'	kQntEmpt'	k@ntEmpt'	k@ntEmpt'
design	Prefix W–S	dIz2n'	diz2n'	dIz2n'	diz2n'	NR*	dIsIn'	dIz2n'
disgrace	Prefix W–S	dIsgr1s'	dIsgr1s'	dIsgr1s'	dIsgr1s'	dIsgr1s'	dIsgr1z'	dIsgr1s'
enforce	Prefix W–S	Enf9s'	Inf9s'	Inf9s'	Inf9s'	Inf9s'	Inf9z'	Inf9'
explain	Prefix W–S	Ekspl1n'	Ekspl1n'	Ekspl1n'	Eks1n'	NR*	Ekspl1n'	Ikspl1nd'
improve	Prefix W–S	Impruv'	Impruv'	Impr5v'	Impruv'	Impruv'	Impr5v'	Impruv'
inform	Prefix W–S	Inf9m'	Inf9m'	Inf9m'	Inf9m'	Inf9m'	Inf9m'	Inf9m'
inspire	Prefix W–S	Insp2r'	Insp'2@*	Insp2r'	Insp'2@*	Insp2r'	'Insp2@r	Insp7'
intact	Prefix W–S	Int{kt'	Int{kt'	Int{kt'	Int{kt'	Int{kt'	Int{kt'	Int{kt'
intense	Prefix W–S	IntEns'	IntEns'	IntEns'	IntEst'	IntEns'	IntEnz'	In@ns'
preside	Prefix W–S	prIz2d'	prIs2d'	prIs2d'	prIs2d'	prIs2d'	prIs2d'	prEsId'
proclaim	Prefix W–S	crQkl1m'	pr5kl1m'	prQkl1m'	pr5kl1m'	pr5kl1m'	pr@kl1m'	'prQkl1m
prolong	Prefix W–S	prQlQN'	pr5lQN'	pr5lQN'	pr5lQN'	pr5lQN'	pr@lQN'	'pr5lQN
rejoin	Prefix W–S	rI_4n'	ri_4n'	rI_4n'	ri_4n'	ri_4n'	rI_4n'	rI_4n'
remind	Prefix W–S	rIm2nd'	rIm2nd'	rIm2nd'	rIm2nd'	rIm2nd'	rImInd'	rImInd'
remove	Prefix W–S	rImuv'	rimuv'	rIm5v'	rimuv'	rIv5v'	rIm5v'	rImuv'
return	Prefix W–S	rIt3n'	rIt3n'	rIt3n'	rIt3n'	rIt3n'	rIt3n'	rEt@n'
reveal	Prefix W–S	rIvil'	rIvil'	rIvil'	rIvil'	rIvil'	rIvil'	rIvil'
subtract	Prefix W–S	sVbtr{kt'	sVmbr{kt'	'sVbtr{kt	sVbtr{kt'	sVbtr{kt'	s@btr{kt'	'sVbtr{kt
surpass	Prefix W–S	s3p{s'	s3pVs'	s3p{s'	s3p{s'	's3pVs	's3p{ss	's3p#s
admit	Prefix W–S	@dmIt'	{dmIt'	@dmIt'	{dmIt'	'{dmIt	@dmIt'	'{dmIt
adopt	Prefix W–S	@d5p'	@d{pt'	@dQpt'	'dQpt	@dQpt'	@dQpt'	@dQpt'
agree	Prefix W–S	{gri'	@gri'	@gri'	@gri'	@gri'	@gri'	@gri'
aloof	Prefix W–S	@luf'	@lVf'	@luf'	@fluf'	@luf'	@luf'	@luf'
conclude	Prefix W–S	kQnkljud'	kQnklud'	kQnklud'	kQnlug'	kQnklud'	k@nklud'	k@@dd'*
consult	Prefix W–S	'kQnsVlt	kQnsVlt'	'kQnsVlt	'kQnsVlt	kQnsVlt'	k@nsVlt'	kQnsVlt'
decide	Prefix W–S	dIs2d'	dIs2d'	dIs2'd@d*	dIs2d'	dIs2d'	dIs2d'	dIs2d'
discreet	Prefix W–S	dIskrit'	dIskrit'	dIskrit'	dIskrit'	dIskrit'	dIskrit'	dIskrit'
endure	Prefix W–S	Endj9'	Indj9'	Endju'	Indj9'	Indj9'	Ind9'	Endj'*
exploit	Prefix W–S	Ekspl4t'	Ekspl4t'	'Ekspl4t	Ekspl5t'	Ekspl4t'	Ekspl4t'	Ikspl4t'
immune	Prefix W–S	Imun'	Imun'	Imjun'	NR*	Imjun'	Immjun'	Imjun'

(*continued on next page*)

– *(continued)*

Stimulus	Condition	Patient					Model	
		1	2	3	4	5	RC00	CDP++
include	Prefix W–S	Inkljud'	Inkljud'	'Inklud	Inkljud'	Inkljud'	Inklud'	Inkudd'
insist	Prefix W–S	InsIst'	InsIst'	InsIst'	InsIst'	InsIst'	InsIst'	InsIst'
invade	Prefix W–S	Inv1d'	Inv1d'	Inv1d'	Inv1d'	Inv1d'	Inv1d'	Inv1d'
invoke	Prefix W–S	Inv5k'	Inv5k'	Inv5k'	Inv5k'	Inv5k'	Inv5k'	Inv5k'
precise	Prefix W–S	prIs2s'	prEsis'	prIs2s'	pris'Es@*	pris2s'	prIs2z'	'prEsIs
promote	Prefix W–S	pr@m5t'	prQmt5'	pr@m5t'	prQm'EtI*	pr@m5t'	pr@m5t'	pr@m5t'
protect	Prefix W–S	prQtEkt'	pr5tEkt'	'prQ_Ekt	pr5tEst'	pr5tEkt'	pr@tEkt'	'prQtEkt
reduce	Prefix W–S	rIdjus'	rIdjus'	rIdjus'	rIdVs'	rIdjus'	rIdjuz'	rIdjus'
reflect	Prefix W–S	rIflEkt'	riflEkt'	riflEkt'	riflEks'	riflEkt'	rIflEkt'	rIflEkt'
regime	Prefix W–S	rI_2m'	ri_2m'	rI_im'	ri_2m'	'rE_1m	rIg2m'	rI2m'
resist	Prefix W–S	rIsIst'	rizIst'	riInsIst'	rizIst'	rizIst'	rIsIst'	rIzIst'
revenge	Prefix W–S	rIvEn_'	rIvEn_'	rIvEn_'	rIvEn_'	rIvEn_'	rIvEn_'	rIvEn_'
submit	Prefix W–S	sVbmIt'	'sVbmIt	s@bmIt'	sVbmIt'	'sVbmIt	s@bmIt'	'sVbmIt
survive	Prefix W–S	s3v2n'	s3v2v'	s3v2v'	s3v2v'	s3v2v'	's3vIv	's3vIv
adverse	Prefix S–W	{dv3s'	{dv3s'	{dv3s'	'{dv3s	{dv3s'	@dv3z'	{dv3z'
agate	Prefix S–W	{g1t'	@g1t'	{g1t'	Non Int.*	@g1t'	@g1t'	{g1t'
agent	Prefix S–W	{gEnt'	1_Ent'	'1_Ent	'1_@nt	1nJEnt'	@_Ent'	1_Ent'
atoll	Prefix S–W	@tQl'	@t5l'	'{tQl	@t5l'	@t5l'	@tQl'	'{t5l
context	Prefix S–W	kQntEkst'	kQntEkst'	'kQntEkst	kQntEkst'	kQntEkst'	k@ntEkst'	'kQntEkst
convent	Prefix S–W	kQnvEnt'	kQnvEnt'	'kQnv3t	kQnvEkt'	'kQnv@nt	k@nvEnt'	'kQnv@nt
depot	Prefix S–W	dEpQt'	dEpQt'	dIpQt'	'dEpQt	dip5t'	dIpQt'	'dEpQt
discord	Prefix S–W	dIsk9d'	dIsk9d'	dIsk9d'	dIsk9d'	dIsk9d'	dIsk9d'	dIsk9d'
entrails	Prefix S–W	Entr1lz'	Entr1ls'	Ent1lz'	Entr1ls'	Entr1ls'	Intr1lz'	intr1lz'
expert	Prefix S–W	Eksp3t'	Eksp3t'	Eksp3t'	Eksp3t'	Eksp3t'	Eksp3t'	'Eksp3t
impulse	Prefix S–W	ImpVls'	ImpVls'	ImpVls'	ImpVls'	ImpVls'	ImpVlz'	ImpVls'
income	Prefix S–W	Ink5m'	InkVm'	'INkVm	InkVm'	InkVm'	Ink5m'	Ink5m'
inland	Prefix S–W	'Inl{nd	Inl{nd'	'Inl@nd	'Inl@nd	'Inl{nd	Inl{nd'	Inl@nd'
input	Prefix S–W	'InpVt	InpVt'	'InpVt	pVt5t'	InpVt'	InpVt'	'InpVt
insight	Prefix S–W	Ins2t'	Ins2t'	'Ins2t	Ins2t'	Ins2t'	Ins2t'	Ins2t'
pretext	Prefix S–W	prItEkst'	prEtEkst'	prItEkst'	prit{ks'	pritEkst'	prItEkst'	'prEtEkst
product	Prefix S–W	prQdVkt'	'prQdjus	'prQdVkt	'prQdVkt	'prQdVkt	pr@dVkt'	'prQdVkt
program	Prefix S–W	prQgr{m'	'pr5gr@m	'prQgr@m	'pr5gr{m	'pr5gr@m	pr@gr{m'	'prQgr@m
recent	Prefix S–W	risEnt'	risEnt'	'risEnt	risEnt'	rIsEnt'	rIsEnt'	rIEnt'
reflex	Prefix S–W	rIflEkt'	riflEks'	'riflEks	riflEks'	riflEks'	rIflEks'	'riflEks
regent	Prefix S–W	ri_Ent'	ri_Ent'	ri_Ent'	ri_Ent'	'ri_Ent	rI_Ent'	rI_Ent'
respite	Prefix S–W	rIsp2t'	risp2d'	rIsp2t'	risp2t'	risp2t'	rIsp2t'	rIsp2t'
retail	Prefix S–W	rIt1l'	rit1l'	'rit1l	rit1l'	rit1l'	rIt1l'	rit1l'
subway	Prefix S–W	s@bw1'	sVbw1'	'sVbw1	sVbw1'	'sVbw1	s@bw1'	'sVbw1
surface	Prefix S–W	s3f1s'	's3f*	's3f1s	's3f1s	s3f1s'	's3f1z	's3f1s
adjunct	Prefix S–W	@d_VNkt'	{d_Vnkt'	{d_VNkt'	'{d*	{d_Vnkt'	@d_VNkt'	@_VNkt'
apron	Prefix S–W	'{prQn	1prQn'	'1prQn	'1pr@n	'1prQn	@prQn'	@pr@n'
aspect	Prefix S–W	{spEkt'	@spEkt'	{spEkt'	QspIt'	'{sbEkt	@spEkt'	{spEkt'
athlete	Prefix S–W	{Tlit'	{Tlit'	{TlE'tIk*	{Tlit'	{Tlit'	@Tlit'	{Tl1t'
concert	Prefix S–W	kQns3t'	kQns3t'	'kQns3t	'kQns3t	'kQns3t	k@ns3t'	'k5n@t
congress	Prefix S–W	kQngrEs'	kQngrEs'	'kQngrEs	'kQngrEs	kQngrEs'	k@ngrEs'	'kQNgrIs
denim	Prefix S–W	'dEnIm	dEnIm'	'dEmIn	'dEmIn	dinIm'	dInIm'	'dEnIm
distant	Prefix S–W	dIst{nt'	dIst{nt'	'dIst@nt	dIst{nt'	'dIst@nt	dIst{nt'	'dIst@nt
enzyme	Prefix S–W	Enz2m'	Enz2m'	Enz2m'	'Enz2m	Enz'2mIn*	'Enz2m	Enz2m'
exile	Prefix S–W	Eks2l'	Ekz2l'	Eks2l'	Ekz2l'	Ekz2l'	Egz2l'	Eks2l'
impasse	Prefix S–W	Imp{s'	Imp1s'	Imp{s'	Imp1s'	Imp{s'	Imp{si'*	Imp#s'
index	Prefix S–W	IndEks'	IndEks'	'IndEks	IndEks'	IndEks'	IndEks'	'IndEks
infant	Prefix S–W	Inf{nt'	Inf{nt'	'Inf@nt	'Inf@nt	'Inf@nt	Inf{nt'	Inf{nt'
injure	Prefix S–W	In_9'	In_j9'	In_j9'	'In_@	In_j9'	In_9'	In_'*
instinct	Prefix S–W	InstInkt'	'InstItIt*	'Inst@nt	'InsVnt	'InstInkt	InstINkt'	InstINkt'
prelude	Prefix S–W	prIljud'	priljud'	'prIljud	priljud'	priljud'	prIlud'	prEljud'
problem	Prefix S–W	'pr5blEm	'prQbl@m	'prQblEm	'prQbl@m	'prQbl@m	pr@blEm'	'prQbl@m
prospect	Prefix S–W	prQspEkt'	PrQpQspEkt*	prQspEkt'	prQpEs'	prQspEkt'	pr@spEkt'	'prQspEkt
refuge	Prefix S–W	rIfju_'	rIfju_'	rIfju_'	rIfju'	rIfju_'	rIfju_'	rIfju_ '
relic	Prefix S–W	'rElIk	'rilIk	ris2kl'	rElIk'	'rilIk	rIlIk'	'rIlIk
relish	Prefix S–W	rElIS'	rElIS'	'rElIS	'rElIS	rilIS'	rIlIS'	'rElIS
rescue	Prefix S–W	rIskju'	rIskju'	riskj9'	rIskju'	'rEskju	rIskju'	'rEzk*
revel	Prefix S–W	rIvEl'	rivEl'	rivEl'	riv2l'	rivEl'	rIvEl'	'rEv@l
suburb	Prefix S–W	sVb3b'	sub3b'	'sVb3b	sub3b'	sub3b'	s@b3b'	'sVb3b
survey	Prefix S–W	s3v1'	s3v1'	's3v1	's3v1	s3v1'	's3v2	's3vI

– *(continued)*

Stimulus	Condition	Patient					Model	
		1	2	3	4	5	RC00	CDP++
bishop	NoPrefix S–W	'bIS@p	'bISQp	'bIS@p	'bISQp	'bISQp	'bIS@p	'bISQp
borough	NoPrefix S–W	bQr6'	'b3@	'b{r@	NR*	'b3@	'b9@9	'b9r*
chemist	NoPrefix S–W	'kEmIst	'kEmIst	'kEmIst	'tEmIst	NR*	'JEmIst	'JEmIst
climate	NoPrefix S–W	kl2m1t'	klIm1t'	'kl2m1t	'kl2m@nt	'kl2m1t	klIm1t'	'klIm1t
donkey	NoPrefix S–W	'dQNki	'dQnki	'dQNkI	'dQnki	'dQnki	'dQNk1	'dQnkI
famine	NoPrefix S–W	f@m2n'	'f{mIn	'f{mIn	'f{mIn	'f{mIn	'f{m2n	'f{m2n
fortress	NoPrefix S–W	'f9trEs	f9trEs'	'f9trEs	'f9trEs	'f9trEs	f@trEs'	'f9trIs
margin	NoPrefix S–W	'm#_In	'm#gIn	'm#_In	'm#_In	'm#_In	'm#gIn	'm#_In
merchant	NoPrefix S–W	'm3J{nt	'm3J@nt	'm3J@nt	'm3J@nt	'm3J@nt	'm3J@nt	'm3J@nt
message	NoPrefix S–W	mEs1_'	'mEs1_	'mEsI_	'mEsI_	'mEs1_	'missI_	'mEsI_
monarch	NoPrefix S–W	mQn#J'	mQn#J'	'mQn#k	mQn'#ki*	'mQn@k	'mQn@J	'mQn@k
orchard	NoPrefix S–W	'9J#d	'9J3d	'9J@d	'9J3d	'9J3d	'9J@d	'9J#d
palace	NoPrefix S–W	p{l1s'	'p{l@s	'pl1s	'p{l1s	'pVl1s	'p{l1z	'p{l@s
parent	NoPrefix S–W	'p#{nt	'p8@nt	'p{r@nt	'p8@nt	'p8@nt	'p#@nt	'p#r@nt
porridge	NoPrefix S–W	p9I_'	'pQrI_	'pQrI_	'pQrI_	'pQrI_	'p9rI_	'pQrI_
purpose	NoPrefix S–W	p3p5z'	'p3pQs	'p3p@s	'p3sp@s	'p3p@s	p3p5z'	'p3p5z
silent	NoPrefix S–W	's2l@nt	's2lEnt	's2l@nt	's2lEnt	's2lEnt	's2l@nt	'sIl@nt
tactic	NoPrefix S–W	't{ktIk	't{ktIk	't{ktIk	NR*	NR*	't{ktIk	't{stIk
talent	NoPrefix S–W	t@l{nt'	't{lEnt	't{l@nt	't{lEnt	't{lEnt	't1l@nt	't{l@nt
textile	NoPrefix S–W	tEkst2l'	'tEkst2l	'tEkst2l	'Ekst2l	'tEkst2l	'tEkst2l	'tEkst2l
toilet	NoPrefix S–W	't4lEt	't4lEt	't4lEt	't4lEt	't4lEt	't4lIt	't4lIt
twilight	NoPrefix S–W	'tw2l2t	tw2l2t'	'tw2l2t	'tw2l2t	'tw2l2t	'twIl2t	'twIl2t
urban	NoPrefix S–W	'3b@n	'3bVn	'3b@n	'3bVn	NR*	'3b@n	'3b@n
walnut	NoPrefix S–W	'w{lnVt	'w9lnVt	'w{lnVt	'w9lnVt	'w9lnVt	'w{lnVt	'w9lnVt
welcome	NoPrefix S–W	'wElk@m	'wElk@m	wElk@m	'wElk@m	'wElk@m	'wElk5m	wElk5m'
biscuit	NoPrefix S–W	bIskjut'	'bIsk@t	'bIskIts	'bIsk@t	NR*	'bIskut	'bIskIt
campus	NoPrefix S–W	'k{mp@s	'k{mpVs	'k{mpVs	'k{mpVs	k{mpVs'	'k{mpuz	'k{mp
chapel	NoPrefix S–W	'J{p@l	'_{p@l	'J{p@l	'_{p@l	'_{p@l	'J1p@l	'J1p@l
culture	NoPrefix S–W	kVltj9'	'kVlJ9	'kVlJ9	'kVlJ9	NR*	'kVlt9	'kVlt@
diamond	NoPrefix S–W	d2mQnd'	'd2j@mQnd*	d2m@nd	'd2m@nd	'd2mQnd	'dI@mQnd	'dI@m
fountain	NoPrefix S–W	f6nt1n'	f6nt1n'	'f6nt1n	f6nt1n'	'f6nt@n	'f6nt1n	'f6nt1n
fragile	NoPrefix S–W	fr{_2l'	'fr{_2l	'fr{_2l	'fr{_2l	'fr{_2l	'fr{g2l	'fr{_2l
frequent	NoPrefix S–W	frEkwEnt'	frEkwEnt'	'frikwEnt	'frEkwEnt	NR*	'frEku@nt	'frEkw@nt
garbage	NoPrefix S–W	k#b1_'	'g#r{_	'g#b1_	'g#bI_	'g#b1_	'g#bI_	'g#bI_
helmet	NoPrefix S–W	'hElmEt	'hElmEt	'hElm@t	'hElmEt	'hElmIt	'hElmIt	'hElmIt
lettuce	NoPrefix S–W	'lEtVs	lEtjus'	'lEtVs	'lEt@s	'lEtIs	'lEtjuz	'lEtus
minute	NoPrefix S–W	mInjut'	mInjut'	'mIn@t	mInut'	'mInIt	mInjut'	'mInjut
mountain	NoPrefix S–W	m6nt1n'	'm6nt1n	'm6nt1n	'm6nt@n	'm6nt@n	'm6nt1n	'm6nt1n
mustard	NoPrefix S–W	mVst#d'	'mVst#d	'mVst@d	'mVst#d	'mVst#d	'mVst@d	'mVst@d
pattern	NoPrefix S–W	p{t3n'	'p{t3n	'p{t3n	'p{t3n	'p{t3n	'p{t3n	'p{t@n
pigeon	NoPrefix S–W	'pI_Vn	pI_Vn'	'pI_@n	'pI_Vn	'pI_@n	'p2_@n	'p2_*
portrait	NoPrefix S–W	p9tr1nt'	p9tr1t'	'p9tr@t	'p9tr1t	p9tr1t'	'p9tr1t	'p9tr1t
publish	NoPrefix S–W	'pVblIS	'blIS*	'pVblIS	'pQlIS	'pVbIS	'pVblIS	'pVblIS
robot	NoPrefix S–W	'rQb@t	'r5bQt	r5bQt'	'r5bQt	'r5bQt	'rQb@t	'r5bQt
scandal	NoPrefix S–W	'sk{nd@l	'sk{nd@l	'sk{nd@l	'sk{nd@l	'sk{nd@l	'sk{nd@l	'sk{nd@l
spinach	NoPrefix S–W	spIn{J'	spInIJ'	'spIn@S	'spInIJ	spIn1k'	'spIn@J	'spIn@k
trolley	NoPrefix S–W	'tr5li	'trQli	'trQlI	'trQli	'trQli	'trQl1	'trQlI
verdict	NoPrefix S–W	'v3dIkt	'v3dIk	'v3dIkt	'v3dIkt	'v3dIkt	'v3dIkt	'v3dIkt
volume	NoPrefix S–W	'vQljum	'vQlEm	'vQljum	'vQljum	'vQljum	'vQlum	'vQlj@m
window	NoPrefix S–W	'wInd5	'wInd5	'wInd5	'wInd5	'wInd5	'wInd5	'wInd5

Note. Non-Int. = Non-Intelligible; NR = No Response * = Not included in the statistical analyses.

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