An investigation of grapheme parsing and grapheme-phoneme knowledge in two children with dyslexia

Larsen, Linda, Kohnen, Saskia, McArthur, Genevieve and Nickels, Lyndsey

POST-PRINT VERSION 16.01.2018

An Investigation of Grapheme Parsing and Grapheme-Phoneme Knowledge in Two Children with Dyslexia

Linda Larsen

University of Oslo and Macquarie University

Saskia Kohnen, Genevieve McArthur and Lyndsey Nickels

Macquarie University

Author Note

Linda Larsen, Department of Special Needs Education, University of Oslo; Linda Larsen, Saskia Kohnen, Genevieve McArthur and Lyndsey Nickels, ARC Centre of Excellence in Cognition and its Disorders, Department of Cognitive Science, Macquarie University.

We would like to thank JC, JW, and their parents for their participation in this research. We thank the control participants, teachers, Heads of Primary, and Principals at the Norwest Christian College, Redfield College, and St Peter's Anglican Primary School for their involvement in the study. We also thank Stephen Pritchard for helpful discussion and comments on connectionist computational models of word reading. Lastly, we thank the Editor and two anonymous Reviewers for constructive suggestions and comments.

This paper was prepared while Linda Larsen was funded by a Postdoctoral Fellowship, Saskia Kohnen was funded by a Macquarie University Research Fellowship (MQRF), Genevieve McArthur was funded by an ARC Australian Research Fellowship (0879556), and Lyndsey Nickels was funded by an ARC Future Fellowship (120100102).

Correspondence regarding this article may be sent to L. Larsen, Department of Special Needs Education, University of Oslo, PO Box 1140, 0318 Oslo, Norway (email: linda.larsen@isp.uio.no).

Correspondence regarding this article may be sent to L. Larsen, Department of Special Needs Education, University of Oslo, PO Box 1140, 0318 Oslo, Norway (email: linda.larsen@isp.uio.no).

Abstract

The aim of this study was to understand the relationship between children's knowledge of letter-sound rules ("grapheme-phoneme knowledge") and their ability to identify separate graphemes (e.g., SH, OI) that comprise words ("grapheme parsing"). We used a single-case study approach with children with phonological dyslexia who were able to read words accurately via whole-word processes ("lexical reading"), but were not able to read using grapheme-phoneme knowledge ("non-lexical reading"). These children were able to correctly parse some graphemes without grapheme-phoneme knowledge for these graphemes. However, they were unable to correctly parse some graphemes for which they had grapheme-phoneme knowledge. This dissociation suggests that children may acquire grapheme-phoneme knowledge and phoneme parsing independently. We discuss the implications of these findings for cognitive models of word reading.

Keywords: non-lexical reading, grapheme-phoneme knowledge, grapheme parsing, phoneme blending, case-study

An Investigation of Grapheme Parsing and Grapheme-Phoneme Knowledge in Two Children with Dyslexia

A number of theories have been proposed to explain how people learn to read words accurately. One theory – *the self-teaching hypothesis* (Share, 1995, 2008) – suggests that letter-sound rules (“grapheme-phoneme correspondence knowledge”) are used to recode the letters of an unknown word into speech sounds (“phonological recoding”). The repeated phonological recoding of an unknown word leads to the development of a visual memory of that written word (and its pronunciation) such that it becomes “known” (“visual word recognition”; Stuart & Stainthorp, 2016). Although popular, this theory does not specify the cognitive processes that are involved in phonological recoding or visual word recognition. This makes the self-teaching hypothesis a less useful theoretical framework for understanding one of the key sub-skills for children’s early reading, namely, the ability to translate graphemes to their associated phonemes.

Another influential theoretical framework for word reading is the *dual-route theory* of reading aloud (e.g., Coltheart, 1985; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Perry, Ziegler, & Zorzi, 2007; Zorzi, Houghton, & Butterworth, 1998). As the name implies, the dual-route theory proposes two processing routes for converting a string of letters into a spoken response – the lexical route (via visual word recognition) and the non-lexical route (via phonological recoding). Figure 1 depicts a standard representation of the dual-route framework, where different boxes represent the different cognitive processes (components), and arrows represent the flow of information between the different components (e.g., Coltheart, 1985, 2006; Newcombe & Marshall, 1984; Temple, 1985).

[Insert Figure 1 about here]

Like most standard depictions of the dual-route model of reading, Figure 1 does not include two potential components of the non-lexical route – *grapheme parsing* and *phoneme blending*. Specifically, when attempting to read an unknown word (e.g., DAUB) or nonword (e.g., FOIM), the letters in the letter-string need to be “parsed” into chunks of one or more letters (graphemes) that each represent a single speech sound ("grapheme parsing"; Brunsdon, Hannan, Nickels, & Coltheart, 2002; Coltheart et al., 2001; Mitchum & Berndt, 1991; Newcombe & Marshall, 1984; Temple, 1985). For example, DAUB would be parsed into D – AU – B. Following grapheme parsing, each grapheme is mapped onto its speech sound (phoneme) using grapheme-phoneme correspondence knowledge ("GPC knowledge"). These phonemes are then blended together into a single word "daub" ("phoneme blending") prior to articulation.

While rarely depicted as separate components, the grapheme parsing and phoneme blending components are often assumed in dual-route models. For example, Pritchard, Coltheart, Palethorpe, and Castles (2012) implement grapheme parsing computationally in the form of a 4-slot window that moves serially across the letter-string from left to right. Berndt, Haendiges, Mitchum, and Wayland (1996) suggest a phoneme blending process that involves articulatory constraints similar to those involved in speech production. Figure 2 shows a dual-route model in which grapheme parsing and phoneme blending are represented as separate components to GPC knowledge in the non-lexical route (e.g., Mitchum & Berndt, 1991).

[Insert Figure 2 about here]

In contrast to the self-teaching hypothesis (Share, 1995, 2008), which is a theory about how children transition from using phonological decoding (a more laborious reading strategy) to visual word recognition (an automatic and quick reading strategy), dual-route models of reading aim to provide a framework that explain characteristics of typical and atypical reading. Further, in dual-route models of reading, the cognitive processes involved in reading, and the relationships between them, are clearly specified. This is important as it is then possible to develop and test explicit hypotheses about the cognitive processes involved in word reading. It is also possible to computationally implement dual-route models of reading. Two examples of such implementations are the Dual-Route Cascaded (DRC) model of reading aloud and word recognition (Coltheart et al.,

2001) and the Connectionist Dual-Process Plus (CDP+) model (Perry et al., 2007)[1]. The fact that dual-route models of reading are clearly specified in terms of structure and not merely descriptive in nature, and also allow for the assessment of explicit hypotheses, makes dual-route models of reading an ideal framework for the current study. This study sought to further our understanding of GPC knowledge, and how this knowledge is related to other sub-skills involved in phonological decoding (i.e., non-lexical reading).

A number of single case studies with selective impairments in components of the non-lexical reading route have been reported in the literature (e.g., Beauvois & Derouesné, 1979; Berndt, et al., 1996; Derouesné & Beauvois, 1985; Goodall & Phillips, 1995; Newcombe & Marshall, 1985; Patterson & Marcel, 1992). However, to our knowledge, no study has examined the relationship between the separate components of the non-lexical route. In particular, it is not yet known if grapheme parsing and GPC knowledge develop independently.

We know from previous studies that children with phonological dyslexia have poor GPC knowledge (e.g., Brunsdon et al., 2002; Temple & Marshall, 1983). However, according to the dual-route theory, phonological dyslexia could also arise from a deficit in grapheme parsing or phoneme blending or GPC knowledge, or a combination of these. Here, we are most concerned with impairments of grapheme parsing and their possible independence from GPC knowledge. For example, in order to parse the graphemes in FOIM (i.e., F – OI – M), the reader needs to process OI as a multi-letter grapheme rather than two single-letter graphemes (i.e., O – I). According to dual-route theory, this grapheme parsing is purely orthographic: A child may know that the letters O and I form the grapheme OI without knowing the corresponding phoneme /ɔɪ/ (as in COIN). Such grapheme parsing knowledge could be learned via repeated co-occurrence of these letters in the words to which a child is exposed. If it is true that grapheme parsing and GPC knowledge are

---

[1] While both DRC and CDP+ are computational implementations of dual-route theory, we note that they differ in their architecture and particularly in the way in which graphemes are translated into phonemes. For DRC, this process is rule-based and hard-wired into the model, whereas for CDP+ the process is statistical and must be learned by the model. Put in a different way, DRC uses a look-up procedure where there is a one-to-one relationship between graphemes and phonemes, while CDP+ uses a connectionist two-layer associative network to learn which graphemes are associated with which phonemes and thus, there is a many-to-many relationship between graphemes and phonemes.

acquired independently, then it should be possible for a child to parse a grapheme without knowing its associated phoneme mapping, and vice versa. However, it is also possible that correct parsing of a multi-letter unit is only possible once the phoneme mapping for that multi-letter unit has been acquired. That is, children may only be able to parse a multi-letter grapheme correctly if the corresponding phoneme mapping is already known. If this were true, grapheme parsing is a reflection of GPC knowledge, and hence the two abilities will not dissociate.

The primary aim of this study is to determine whether or not grapheme parsing and GPC knowledge are separate and independent components of the non-lexical reading system. To this end, we addressed two questions: (1) can parsing of a multi-letter grapheme be intact if its corresponding phoneme mapping is not known; and (2) can parsing of a multi-letter grapheme be impaired if its corresponding phoneme mapping is known? We used multi-letter graphemes (e.g., OI) rather than single-letter graphemes (e.g., O) because correct grapheme parsing of multi-letter graphemes retain the multi-letter unit (e.g., OI), whereas incorrect grapheme parsing would result in two separate units (e.g., O and I).

A secondary aim of this study was to test two predictions of the dual-route theory regarding non-lexical reading by asking two questions, namely: (1) can nonwords containing graphemes with unknown phoneme mappings be read correctly; and (2) do children with phonological dyslexia have difficulties with grapheme parsing or phoneme blinding as well as poor GPC knowledge? These questions can be thought of more as measurement questions trying to explain the characteristics of typical and atypical reading (whereas our first set of questions are more theoretical in nature). The functioning of the non-lexical route is often tested using nonword reading (i.e., fictitious words that follow the GPC rules, e.g., FOIM), which are novel to all readers regardless of their reading experience. According to dual-route theory, if there is a breakdown in the GPC knowledge component of the non-lexical route, then nonword reading should be impaired. For example, if a child’s knowledge of the mapping between the grapheme OI and its corresponding phoneme /ɔɪ/ is impaired, then the nonword FOIM cannot be correctly read aloud. Despite the fundamental nature of this prediction, there are few direct investigations of this claim. One study that did investigate this issue found that children were able to correctly read a nonword (i.e., VOUN) even if they were unable to correctly read all the graphemes in the nonword when each grapheme was presented individually (i.e., V, OU, N; Gilbert, Compton & Kearns, 2011). This has been taken to indicate that children exhibit an ability to use orthographic information of different grain sizes (e.g., single letters, letter clusters, onset-rime; Ziegler & Goswami, 2005), and that implicit GPC knowledge may be sufficient to correctly decode words. However, it is not entirely clear what is meant by implicit GPC knowledge or how this could have aided children in correctly reading the nonword. Another possibility is that this result reflects item-specific performance factors, since the same pattern of performance (i.e., correct nonword reading in the face of incorrect reading of individual graphemes) was not reported for other test items (e.g., TEEK, BOSH). Furthermore, Gilbert et al. scored GPC knowledge dichotomously, such that if all graphemes in a nonword were read correctly in isolation, then GPC knowledge (for that nonword) was given a score of 1 and deemed to be known. On the other hand, if any one grapheme or combination of graphemes in a nonword were not read correctly in isolation, then GPC knowledge (for that nonword) was given a score of 0 and deemed not known. As a consequence of this scoring procedure, it is not possible to determine which grapheme or combination of graphemes was not read correctly in isolation when GPC knowledge was not known.

In the current study, we used a different method that allowed us test our first question regarding non-lexical reading. Namely, we tested if nonwords containing graphemes with unknown phoneme mappings could be read correctly (our first secondary question). In contrast to Gilbert et al. (2011), who generally only tested target GPCs in two nonword items, we ensured that the results were robust by testing more nonword items in each grapheme condition. We also tested our other secondary question regarding which process or processes of the non-lexical reading route are impaired in phonological dyslexia. If non-lexical reading depends on three processes (i.e., grapheme parsing, GPC knowledge and phoneme blending) then some children with phonological dyslexia should have difficulties with any one or any combination of these processes. This is the first investigation, to our knowledge, to explore whether grapheme parsing and GPC knowledge are indeed separate and independent processes of the non-lexical reading route as suggested by dual-route models (Coltheart, 1985; Newcombe & Marshall, 1984; Temple, 1985). Further, as dual-route models of reading offer a framework for explaining characteristics of typical and atypical reading, we ask two additional measurement questions about the characteristics or reading profile of children with developmental dyslexia.

Method

The Macquarie University Human Ethics Committee approved the methods outlined below. Children participated in the study through written parental consent and verbal assent was also obtained from each child at the beginning of each testing session.

Participants

The experimental participants were two boys (JC and JW) with poor non-lexical reading but intact lexical reading (i.e., phonological dyslexia). Selecting children with phonological dyslexia allowed us to investigate (for the first time) if this specific non-lexical reading difficulty can be associated with poor grapheme parsing or poor blending in addition to poor GPC knowledge.

Both participants were assessed by the first author at the University. Four testing sessions were completed that varied in length between 30 and 90 minutes. At the time of their first testing session (T1) JC was 10 years and 6 months old and soon to start Grade 5 (JC’s T1 was in the school holidays before he started Grade 5), and JW was 11 years and 3 months old and in Grade 5. The children were referred to this study based on their scores on the Castles and Coltheart Reading Test 2 (CC2; Castles, Coltheart, Larsen, Jones, Saunders, & McArthur, 2009), which assesses non-lexical reading using nonwords and lexical reading using irregular words. Although this test also includes regular words, regular word reading scores were not used as selection criteria as regular words can be read via either the non-lexical or the lexical reading route. Thus, these scores are not informative for establishing the relative strengths of the non-lexical and lexical reading systems specifically. Both children performed within the average range for CC2 irregular word reading (reported ***z***-scores; JC: -0.21 and JW: -0.80) and well below the average range for CC2 nonword reading (reported ***z***-scores; JC: -2.12 and JW: -1.64).

JC attended an independent primary school in inner city Sydney. His mother reported that JC's motor and language skills development had been normal. At the time of testing JC did not receive extra help with reading at school although his mother did believe her son had difficulties with reading. She explained how JC was able to read his "sight word lists" (which contain a mix of regular and irregular words) from school, but if she changed the order of the words it was a struggle for him to read them indicating that he may be rote learning the list rather than actually learning to read the words. JC's mother did not report a family history of learning difficulty.

JW attended a suburban public primary school in Sydney. His mother reported that JW's motor skills development was normal to somewhat advanced, but his language development had been a little delayed. At the time of testing, JW was receiving extra help at school (up to 2 hours per week) and was also seeing a speech pathologist to help with his reading difficulties. JW's mother reported that a second language was spoken at the family-home (Mandarin), however, when probed, she commented that JW generally preferred to speak English at home and that he and his brother spoke English to one-another. While JW's parents spoke Mandarin to each other at home, they were fully literate in English. JW's mother did not report a family history of learning difficulties and no other family members had reading or spelling difficulties.

The control participants were children with normal reading for their age (*n* = 11). They were selected based on performance within the average range on the Phonemic Decoding and Sight Word Reading sub-tests of the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999) using Australian normative data (Marinus, Kohnen, & McArthur, 2013). The control participants were divided into two groups – one group for each of the participants with phonological dyslexia matched on the number of school-terms completed. Given that children tend to start school at approximately the same age, the dyslexic participants and their respective control group was also matched in terms of chronological age; JC was 10 years and 6 months at the time of T1, while the average age of his control group (*n* = 7) was 10 years 5 months (range 9 years 11 months to 10 years 8 months) and JW was 11 years and 3 months at T1, while the average age of his control groups (*n* = 4) was 11 years and 6 months (range 11 years 2 months to 11 years and 11 months). Further, it was ensured that the control participants in each group were able to correctly produce the phonemes associated with the target graphemes (see Experimental assessment (GPC knowledge) below) of the participant with phonological dyslexia. The experimental assessments were specifically tailored around these GPC mappings (details below) and subsequent analysis compared performance of each participant with phonological dyslexia to their respective control group on these assessments.

Background Assessments

Reading. This was assessed using the Castles and Coltheart Reading Test 2 (CC2; Castles et al., 2009). The CC2 contains a list of 40 regular words, 40 irregular words, and 40 nonwords and administration involves presenting all 120 items in a fixed random order. Each list (i.e., regular words, irregular words, and nonwords) has a stopping rule after 5 consecutive errors, which means that the presentation of, for example, irregular words (e.g., BLOOD) may be discontinued while the presentation of regular words (e.g., NEED) and nonwords (e.g., ROFT) continues either until the end of the list or the stopping rule has been met for that list, whichever occurs first. Scores for each list were expressed as *z* scores (*M* = 0, *SD* = 1).

Phonological processing. We tested four different phonological processing skills. *Phoneme blending* was assessed using a phoneme-blending test devised by the first and second authors. A decision was made to use this test instead of a publically available standardised test, for example the Blending Nonwords sub-test from the Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rachotte, 1999), as it was more extensive (i.e., has more test items) and items increased in difficulty less rapidly. The phoneme-blending test comprised 28 items presented in increasing difficulty. On each trial, children heard a nonword spoken as individual phonemes (e.g., /ʃ/ - /iː/ -

/m/) and were asked to put the sounds together to form a “made-up word” (i.e., SHEEM). Children were provided with corrective feedback on 7 practice trials that were not included in the final test score. A stopping rule was applied after 5 consecutive errors and scores were expressed as the number of correct responses.

Phonological segmentation was assessed using the Sound Segmentation subtest from the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al. 1999). This test comprises 20 items presented in increasing difficulty. On each trial, children heard a nonword (e.g., SHAP) and were asked to say the nonword one sound at a time (i.e., /ʃ/, /æ/, /p/). Children were provided with corrective feedback on practice trials. A stopping rule was applied after 3 consecutive errors and scores were expressed as scaled scores (*M* = 10, *SD* = 3).

Phonological short term and working memory was tested using the Forward and Backward Digit Span subtests of the Wechsler Intelligence Scale for Children 4th Edition (WISC-IV; Wechsler, 2003). Each subtest comprises 8 pairs of test items and the number of digits to be repeated increases as the test progressed. On each trial, the experimenter said a string of single-digits (e.g., 2, 5, 6) and children were asked to repeat exactly what the experimenter had said or repeat backwards what the experimenter had said (i.e., 6, 5, 2). A stopping rule was applied when both test items in a pair were incorrectly repeated and scores were expressed as scaled scores (*M* = 10, *SD* = 3).

Non-word repetition was tested using the Repetition of Nonsense Words subtest from the Developmental Neuropsychology Assessment battery (NEPSY; Korkman, Kirk & Kemp, 1998). This subtest comprises 13 items that increase in length and phonological complexity. Children were asked to repeat a spoken nonsense word (e.g., CRUMSEE) played from an audio recording through a set of speakers. A stopping rule was applied after 4 consecutive errors and scores were expressed as scaled scores (*M* = 10, *SD* = 3).

Non-verbal intelligence. This was tested using the Matrices subtest from the Kaufman Brief Intelligence Test 2 (K-BIT 2; Kaufman & Kaufman, 2004). This subtest has 46 items presented in increasing difficulty. On each trial, children saw a matrix with a piece missing and were asked to select the missing piece from six possible pieces. A stopping rule was applied after 4 consecutive errors and scores were expressed as standard scores (*M* = 100, *SD* = 15).

Vocabulary. *Expressive vocabulary* was tested using the picture-naming task from the Assessment of Comprehension and Expression (ACE6-11; Adams, Cooke, Crutchley, Hesketh, & Reeves, 2001). This has 27 items, including 2 practice items, presented in increasing difficulty. In this task, children were presented with a series of pictures, one at a time, and asked to name each picture. The test has no stopping rule and scores were expressed as scaled scores (*M* = 10, *SD* = 3).

Receptive vocabulary was tested using the Peabody Picture Vocabulary Test (PPVT-IV; Dunn & Dunn, 2007). The test has a total of 228 items that are divided into 19 sets of 12 items each and children start at different entry levels depending on their age. This is a spoken word-picture matching task and on each trial the child saw four pictures and was asked to select the picture that matched the word spoken by the experimenter. A stopping rule was applied after 8 errors in any one set and scores were expressed as standard scores (*M* = 100, *SD* = 15).

A summary of the background assessment measures for JC and JW is shown in Table 1. Here we present percentile rank scores for all standardised tests (i.e., all tests except phoneme blending), where performance between the 16th and the 84th percentile (+/- 1*SD*) is considered in the average range. Both participants had well below average nonword reading while irregular word reading was in the average range for their age, which constituted the selection criteria for entry into this study (a diagnosis of phonological dyslexia). Further, both participants were within the normal range on the background measures with the exception of JC being slightly above the normal range on the K-BIT Matrices (Kaufman & Kaufman, 2004), while JW was slightly below the normal range on the WISC-IV Digit-Span Forward (Wechsler, 2003). Both experimental participants performed at control level accuracy on the phoneme-blending test.

In summary, both children have entirely normal development measured on a range of language and cognitive assessments and for irregular word reading. In terms of the processes in

Figure 2, normal irregular word reading allows us to conclude that each child's lexical route was intact (abstract letter identification, orthographic input lexicon, phonological output lexicon, phonological output buffer). Their good expressive and receptive vocabulary skills allowed us to conclude that their semantic systems were intact. JW showed difficulties with one of the tests that assess phonological processing (digit span forward), while JC scored in the normal range on all phonological processing tasks that were administered to him. Finally, one component of the non-lexical route was intact – phoneme blending. We therefore now concentrate on examining the remaining components of the non-lexical route in more detail – grapheme parsing and GPC knowledge.

[Insert Table 1 about here]

Experimental Assessments

GPC knowledge for individual graphemes. Performance on the Letter-Sound Test (LeST; Larsen, Kohnen, Nickels, & McArthur, 2015) was used to select the experimental stimuli used in the grapheme parsing and GPC knowledge experimental tasks (see below). In this task children had to provide the phoneme associated with 51 single- and multi-letter graphemes. Test items were presented on separate index cards and all 51 items were administered (i.e., the LeST does not have a stopping rule). Children were instructed to say the sound each letter or letter-combination made and received corrective feedback on the first three items on the test. For a correct response on these three items (i.e., a response that matched the target response) the examiner responded: "That is correct". For an incorrect response on these three items (i.e., a response that did not match the target response) the examiner responded: "That is not quite right. The letter [insert letter name] makes the sound [insert target sound]". Throughout the test, if a child responded with a letter's name they were prompted to give the sound. Although many graphemes have more than one corresponding phoneme in English (e.g., EA is most often pronounced /iː/ as in HEAT, but is sometimes pronounced /ɛ/ as in HEAD), only the most frequently occurring correspondence was scored as correct (e.g. for EA /i:/ was scored as correct and /ɛ/ as incorrect; Coltheart et al., 2001). For a full description of the LeST, see Larsen et al. (2015).

The LeST was administered on two occasions, after which we used the results to select four vowel multi-letter graphemes (e.g., EA, OI, AY) for examining grapheme parsing. We selected two vowel multi-letter graphemes for which the child was able to provide the target response on both testing sessions (“known GPCs”) and two vowel multi-letter graphemes for which the child could not provide the target response on either of the two testing sessions (i.e., either they provided a response that was not the target response or responded with “don’t know”; “unknown GPCs”). Vowel graphemes were selected as the children were close to ceiling on consonant graphemes. This is in line with previous research showing that children find vowel graphemes more difficult than consonant graphemes (Fredriksen & Kroll, 1976; Graham, 1980) and in particular, vowel multi-letter graphemes (Gilbert et al., 2011; Larsen et al., 2015; Laxon, Gallagher, & Masterson, 2002). An inspection of both children’s errors on the LeST revealed that errors for multi-letter graphemes did not consist of sounding out the phonemes assigned to both the individual letters in the grapheme (e.g., responding /p/ and /h/ for PH), but there were some (19%) errors that involved sounding the first phoneme in multi-letter graphemes (e.g., /ɛ/ for EA).

Grapheme parsing in nonwords. We constructed two grapheme parsing tests – a line drawing test and an embedded word test – around each child’s *known* and *unknown* GPCs (see Table 2 for the selected vowel multi-letter GPCs for JC and JW). It is important to note that while we use the terms *known* and *unknown*, we are not suggesting that GPC knowledge is entirely present or absent, and acknowledge that this knowledge may be graded. By selecting items that were responded to correctly (or incorrectly) twice (i.e., on two separate testing sessions) we simply wished to increase the likelihood that the children had (or had not) acquired reliable long term memories for these items. The terms *known* and *unknown* are shorthand for this.

[Insert Table 2 about here]

In the line drawing test, children had to indicate the grapheme boundaries in nonwords by drawing lines with a pencil (e.g., F|R|OI|T). For this experiment, a list of 13 nonword items (4-5 letters in length) was constructed separately for each child's two *known* and two *unknown* GPCs (i.e., four lists in total). A list of 26 filler items, 4-5 letters in length and consisting of single-letter graphemes only (e.g., FLOT, SLANK), was also constructed. Test and filler items were presented in a random mixed order and children were instructed to "cut" the nonwords into the "bits" or "pieces" that make it up by drawing lines. It was explained that these pieces could be either "small" (i.e., single-letter graphemes) or "large" (i.e., multi-letter graphemes). Test instructions did not include any reference to grapheme, phoneme, grapheme-phoneme correspondence, letter-sound, or phonogram as this may have led the children to use a phonological strategy to solve the task. Practice trials were conducted to ensure that the children understood what they had to do. The practice started with the experimenter parsing a set of 6 nonwords. In the practice set, each item only differed by one letter from the preceding item (e.g., OS, POS, SPOS, SHOS, SHOAS, SHOAST) and practice sets never included any of the *known* or *unknown* GPCs. The experimenter commented on his/her parsing, saying that s/he cut the nonwords into small (i.e., single letter graphemes) and large (i.e., multi-letter graphemes) pieces. After the child had watched the experimenter, the child completed 5 or 6 practice sets (6 items per set) depending on how quickly they understood the task. Corrective feedback was provided and this involved the experimenter reiterating that some pieces are small and some are large. Once the experimenter was sure that the child had understood (but not necessarily that they had got all practice items correct), feedback was discontinued and the testing began. To ensure that performance was minimally influenced by differences between nonwords in real-word neighbours, we ensured that (1) the number of neighbours was low (mean number of neighbours (standard deviation); JC: 4.08 (2.87) and JW: 3.67 (2.39)); and (2) were matched between nonword conditions as far as possible. Test items were scored as correct if the target multi-letter graphemes were separated correctly irrespective of whether the rest of the nonword was parsed correctly. For example, FROIT parsed both as FR|OI|T and F|R|OI|T was scored as correct.

The embedded word task has previously been used by Berndt and Mitchum (1994) and Brunsdon et al. (2002). In this task, participants have to find and circle an embedded target word in a longer letter-string (e.g., circle LAW when presented with PLAWEN). These studies included one important manipulation: whether the target word splits (violates) a grapheme (e.g., WIN splits AW in HAWINCE) or not (e.g., LAW does not split any graphemes in PLAWEN). These two conditions are referred to as violating and non-violating respectively. The previous studies that have used this task found that people had more difficulty (slower reaction times) in the violating condition (e.g., HAWINCE) relative to the non-violating condition (e.g., PLAWEN). This is thought to reflect the fact that once a reader knows a multi-letter grapheme, they will automatically parse this multi-letter grapheme as a unit, thus finding it harder to identify the word boundary. This pattern is therefore used as evidence for grapheme knowledge being intact. In the present study, we used this task as a supplementary measure of grapheme parsing for JC only, but added to the task a manipulation of GPC knowledge. That is, there were violating and non-violating conditions for JC's two *known* and two *unknown* GPCs. Target words were 3-5 letters in length and these were embedded in letter-strings of 5-8 letters in length. To avoid confounding test performance with word-length, stimuli containing 3-letter targets were presented in a random mixed order (i.e., violating and non-violating and known and unknown GPCs), before 4-letter targets were presented, and finally 5-letter targets were presented. JC was instructed to find an embedded word 3 letters in length (or 4 or 5 letters in length) and circle it. The accuracy (i.e., number of words correctly identified) per condition was calculated. Although JC grasped the task immediately, he nevertheless completed 9 practice items with 3-letter targets and 5 practice items each for 4- and 5-letter targets.

GPC knowledge in nonwords. The same nonwords used in the grapheme parsing line drawing task were used in the nonword GPC knowledge task. An item was never presented in both the grapheme parsing task and the GPC knowledge task in the same test session. The task was to read the nonword aloud and scoring was on the basis of accuracy of the target multi-letter graphemes. Thus, a nonword was scored as having been read correctly if the target multi-letter grapheme was read correctly irrespective of whether the entire nonword was read correctly. For example, reading the nonword YOINT as /wɔɪnt/ would be considered a correct response.

[Insert Table 3 about here]

Results

Below we use the results from the experimental assessments to address our research questions. We first address the relationship between grapheme parsing and GPC knowledge to evaluate the independence of these non-lexical processes. Next we address two predictions of the dual-route model.

Determining If Grapheme Parsing and GPC Knowledge Are Independent Processes

Question 1: Can parsing of a multi-letter grapheme be intact if its corresponding phoneme mapping is not known? To answer this question, we compared accuracy on grapheme parsing in nonwords containing *unknown* multi-letter GPCs (JC: OA and EA and JW: AI and EA) for JC and JW to that of their respective control groups (who correctly pronounced the GPCs in isolation) using modified *t*-tests (SINGLIMS; Crawford & Garthwaite, 2002) designed to compare individual test data with a small control group. Neither JC nor JW were significantly different from controls in grapheme parsing accuracy on the line drawing task for their *unknown* GPCs (see Table 3 for raw scores and SINGLIMS statistics). Our findings suggest that being unable to accurately name the phoneme associated with a multi-letter grapheme does not necessarily impair parsing of that grapheme.

However, it is important to note that both JC and the controls’ performance on the parsing of graphemes in nonwords, was close to or at ceiling. Hence, we may not have detected a difference because our items were not sensitive enough. Consequently, an additional analysis was carried out to further investigate his parsing ability. This analysis used the accuracy data (i.e., number of embedded words correctly identified) from the supplementary embedded word parsing task where JC showed more variability in performance (see Table 4). As noted above, intact grapheme parsing makes it harder to identify target words when they split (or violate) a multi-letter grapheme (e.g., circle ASK when presented with POASKE) versus when they are not (e.g., circle OIL when presented with POILUN). For readers who have poor grapheme parsing abilities, their ability to recognise a target word will not be influenced by whether or not a target word violates a multi-letter grapheme. Hence, if JC had impairment in grapheme parsing, we would predict that his performance would be similar in the violating and non-violating conditions for unknown GPCs (i.e., OA and EA). As there was no difference in JC's ability to identify embedded words between the *known* and *unknown* GPC conditions (Fishers exact test: $z = 0.52$, $p = .60$, two-tailed), we first collapsed the data across *known*/*unknown* GPC conditions. We then compared JC's performance on the violating condition (e.g., POASKE) relative to the non-violating condition (e.g., POILUN) to that of controls using the Revised Standardised Difference Test (RSDT; Crawford & Garthwaite, 2005). The test failed to reach significance ($t = 0.11$, $p = .92$, two-tailed), indicating that the difference between the two conditions for JC is the same as it is for the controls (see Figure 3). This further lends support to the possibility that grapheme parsing can be intact even if the associated phoneme mapping is not known.

[Insert Table 4 and Figure 3 about here]

Question 2: Can parsing of a multi-letter grapheme be impaired if its corresponding phoneme mapping is known? To answer this question, we compared JC and JW's accuracy on grapheme parsing in nonwords for lists of *known* GPCs (JC: OI and AY and JW: OI and OA) to their respective control groups using SINGLIMS (Crawford & Garthwaite, 2002). JC's parsing accuracy for *known* GPC1 (OI) and *known* GPC2 (AY) was not significantly different from control level accuracy. JW's parsing accuracy for *known* GPC1 (OI) was not significantly different from the controls, who showed a great deal of variability on the task for this item. For JW's *known* GPC2 (OA), the control group's performance was at ceiling. In contrast, JW was only able to parse GPC2 correctly on 46% of the trials and a normal approximation binominal sign test showed that JW's performance was statistically no greater than chance, $z = 0.28$ and $p = .61$. Further, running SINGLIMS with a small variance (e.g., $SD = 0.01$) in the control group gives a significant result (*p*

< .001). It is therefore clear that JW was worse than the controls at parsing OA despite being able to provide its associated phoneme when assessed on the LeST (Larsen et al., 2015). Our findings suggest that knowing the phoneme associated with a multi-letter grapheme does not necessarily guarantee correct parsing of this grapheme.

Secondary Aim: Testing Two Predictions of the Dual Route Model

Question 1: Can nonwords containing graphemes with unknown phoneme mappings be read correctly? To answer this question, we compared JC and JW to their respective control groups for accuracy of reading nonwords that contained *unknown* GPCs (JC: OA and EA and JW: AI and EA). Controls were able to read the target multi-letter graphemes correctly in isolation (part of the controls' selection criteria) and in nonwords (i.e., their mean accuracy was at 88% across the 4 nonword lists).

JW's nonword reading accuracy for *unknown* GPC1 (AI) was significantly impaired compared to his control group, which would be predicted since the target graphemes were known to the controls (i.e., the controls correctly read the target graphemes in isolation). However, his nonword reading accuracy for *unknown* GPC2 (EA) was not significantly different to controls.

JC's nonword reading accuracy was significantly lower than controls for both his *unknown* GPCs (OA and EA). The fact that JW was able to read nonwords that contained his *unknown* GPC2 at an age-appropriate level demonstrates that it is possible for multi-letter graphemes to be read correctly in nonwords even when they cannot be produced correctly in isolation.

Question 2: Do children with phonological dyslexia have difficulties with grapheme parsing and/or phoneme blending as well as poor GPC knowledge? Compared to the normative data for Grade 3 (the highest grade for which the LeST has normative data) on the LeST (Larsen et al., 2015) JW's GPC knowledge was below average (*z* = -1.13, %ile = 13), while JC's GPC knowledge was in the low-average range (*z* = -0.79, %ile = 22). However, when JC's performance was compared to his control group, it was significantly lower (JC: 38 and controls: *M* = 47, *SD* =

3.27, $t = -2.58$, $p < .05$). Thus, both JC and JW knew fewer GPCs than what would be expected for their age.

Both JC and JW scored within the accuracy range of their controls on a blending task (JC: 13 and controls: $M = 19.57$, $SD = 5.13$ and JW: 14 and controls: $M = 19.75$, $SD = 7.85$, see Table 1). On the line drawing parsing task, while JC's parsing accuracy was almost at ceiling, JW performed lower overall: combining scores across *known* and *unknown* GPCs, JC performed within the average range of the controls (JC: 51 and controls: $M = 51.57$, $SD = 0.53$), while JW's performance was much poorer than controls (JW: 31 and controls: $M = 46$, $SD = 11.34$) although this did not reach statistical significance.

In summary, both JC and JW had poor GPC knowledge, which is not entirely unexpected as GPC knowledge is important for developing skilled reading and both JC and JW had reading profiles consistent with developmental phonological dyslexia. In terms of blending skills, both JC and JW performed within the normal range and JC's grapheme parsing was also in the normal range. However, JW's grapheme parsing was somewhat impaired.

Discussion

The primary aim of this study was to determine whether grapheme parsing and GPC knowledge are separate and independent components of the non-lexical reading system. To address this aim, we asked: (1) can parsing of a multi-letter grapheme be intact if its corresponding phoneme is not known; and (2) can parsing of a multi-letter grapheme be impaired if its corresponding phoneme is known? The secondary aim of this study was to test two predictions made by the dual-route theory regarding non-lexical reading. To address these predictions, we asked: (1) can nonwords containing graphemes with unknown phoneme mappings be read correctly, and (2) do children with phonological dyslexia have difficulties with grapheme parsing and/or phoneme blending as well as poor GPC knowledge? We addressed these questions by testing the ability of two children with phonological dyslexia to produce phonemes for isolated single- and multi-letter graphemes. We selected multi-letter graphemes for which the children could (*known*) and could not (*unknown*) produce the corresponding target phoneme reliably. We then compared these children's ability to both parse and read *known* and *unknown* graphemes in nonwords. Below we use the outcomes to address each question (and hence aim) in turn.

Determining If Grapheme Parsing and GPC Knowledge Are Independent Processes

Question 1: Can parsing of a multi-letter grapheme be intact if its corresponding phoneme mapping is unknown?

The performance of both children in this study suggests that it is indeed possible to parse a multi-letter grapheme without knowing its corresponding phoneme: Both JC and JW performed at or near ceiling on the grapheme parsing in nonwords task for their *unknown* GPCs (and JC's performance in the embedded word parsing task was not significantly different compared to controls). This suggests that JC and JW have representations for graphemes that are independent of their GPC knowledge. This supports dual-route theories that suggest that grapheme parsing and GPC knowledge are separate components of non-lexical reading (see Figure 2). To our knowledge, this is the first time that this has been demonstrated experimentally.

How can a child parse a grapheme without knowing its corresponding phonemes? One possibility is that children extract information about co-occurring letter sequences from words they are exposed to. For example, the letters E and A co-occur as the letter sequence (or grapheme) EA. We know that children acquire orthographic knowledge about spelling patterns from the onset of their experience with print. Even very young children learning to read English correctly judge the nonword BAFF to be more word-like than the nonword BBAF. This is because doublets (e.g., BB and FF) never occur at the beginning of words in English (Cassar & Treiman, 1997). We can think of this as a form of statistical learning. That is, children show sensitivity to the patterns that exist, in this case in written language, and implicitly acquire knowledge about the written language. It is possible that this may be what allowed the children with dyslexia in this study to correctly parse graphemes despite not knowing the associated phonemes.

A strong interpretation of this explanation implies that children would make parsing errors when parsing consonant clusters, for example parsing BR and ST as single graphemes just as they would for EA. While we did not specifically investigate this point, there were few occasions where the children parsed consonant clusters as one unit (e.g., DREAP parsed as DR – EA – P). It is possible that sensitivity to the co-occurrence of letter sequences may be influenced by bigram frequency and we did find that on average, the bigram frequency for vowel multi-letter GPCs was higher than for consonant clusters (average log-transformed bigram frequency for (unknown) GPCs: 11.90 and consonant clusters: 10.59; Jones & Mewhort, 2004). The slightly higher bigram frequency for GPCs may have increased children's sensitivity relative to consonant clusters, which in turn may have aided correct parsing of GPCs.

Question 2: Can parsing of a multi-letter grapheme be impaired if its corresponding phoneme mapping is known?

For the most part, the children were able to parse multi-letter graphemes when they knew corresponding phoneme mappings. However, JW's performance suggests that it may be possible for parsing of a multi-letter grapheme to be impaired even when its corresponding phoneme mapping is *known*: JW's parsing accuracy was significantly lower than that of his control group for his *known* GPC2 (OA-/əʊ/). JW was able to accurately provide the phoneme /əʊ/ for the grapheme OA when this was presented to him in isolation and in nonwords. This suggests that JW had a representation of the grapheme OA and that this was correctly linked to its corresponding phoneme. However, he was relatively poor at parsing OA in nonwords. This does not fit well with dual-route theories that predict that in order to correctly read graphemes in nonwords, both parsing and GPC knowledge need to be intact.

We feel it is unlikely that this result could be due to task demands or properties of the stimuli: JW received ample practice and corrective feedback on the parsing task and he clearly demonstrated that the task was understood. Another possible explanation for JW's poor grapheme parsing for a *known* GPC may lie in the nature of grapheme representations. It is probable that in

JW’s reading system, as in those of most readers, there are representations of not only the grapheme OA, but also those of O and A. When given a multi-letter grapheme in isolation he may process this as a single unit, activating OA. However, in the context of a nonword, all three graphemes (OA, O, and A) may be equally activated. Therefore, it is a matter of chance whether JW will parse the grapheme correctly as OA or incorrectly into the two single-letter graphemes O and A. How then can he read aloud nonwords correctly when he cannot reliably parse OA? When asked to read the nonword TOAG this could be parsed as either OA, or O and A. If the parsing is of O and A, their corresponding phonemes /ɔ/, and /æ/ will be activated. However, the fact that /tɔæg/ is not a possible sequence of phonemes in English leads an editing system to reject this as a possible response. This editing system may be similar to the re-parse process proposed by Temple (1985) whereby an illegal sequence of phonemes will trigger a re-parse, resulting in this case as a parse of OA and the correct response /təʊg/. Hence monitoring and re-parsing may play a role in producing JW’s greater accuracy in reading aloud than in parsing. Clearly this is speculative, and before drawing any firm conclusions from JW’s pattern of performance, it would be necessary to replicate the finding across different GPCs and children.

Secondary Aim: Testing Two Predictions of the Dual Route Model

We tested two predictions of dual-route theory regarding non-lexical reading. According to dual-route theory, if the GPC knowledge component of the non-lexical route is impaired, then nonword reading should also be impaired. We tested this prediction by investigating whether nonwords containing graphemes with *unknown* GPC mappings could be read correctly. Dual-route theory also predicts that non-lexical reading depends on three processes (i.e., grapheme parsing, GPC knowledge and phoneme blending). If this prediction is true, then some children with poor non-lexical reading (i.e., phonological dyslexia) should have difficulty with any one or any combination of these processes. We addressed this prediction by assessing whether the children with phonological dyslexia in this study, had additional difficulties with grapheme parsing and/or phoneme blending in addition to poor GPC knowledge.

Question 1: Can nonwords containing graphemes with unknown phoneme mappings be read correctly?

We investigated whether it is possible to correctly read multi-letter graphemes in nonwords when these cannot be successfully produced in isolation. Dual-route theory (Coltheart, 1985, 2006; Coltheart et al., 2001; Mitchum & Berndt, 1991) predicts that this should not be possible. In line with this prediction, children were significantly worse at reading (three out of four) *unknown* graphemes in nonwords than controls. However, JW read the fourth target grapheme correctly in 70% of nonwords, which was comparable to the performance of his control group. It is also worth noting that, despite performance being significantly worse than controls, both children with dyslexia were able to correctly read their *unknown* GPCs in *some* nonwords. This indicates that it is possible to read multi-letter graphemes correctly in nonwords when they cannot be reliably produced in isolation and lends further support to what Gilbert et al. (2011) found in their study. To arrive at an explanation for how this may be possible we will start by exploring what it means for a GPC to be *known*.

In order to say that a GPC is *known*, this knowledge needs to be demonstrated. A seemingly pure and frequently used method for assessing GPC knowledge is to show readers graphemes in isolation and ask them to produce the sound that each grapheme makes. However, it is possible that sounding out graphemes in isolation does not always tap into the process that is used when reading graphemes in the context of nonwords. In contrast to the relatively automatic assignment of phonemes to graphemes in nonwords, sounding out graphemes in isolation may be a more artificial metalinguistic task, particularly for individuals beyond the primary school years. For example, young adults are able to read graphemes in the context of nonwords such as novel brand-names (e.g., a new drug Zartec), but tend to have difficulties when asked to sound out graphemes in isolation. We have preliminary evidence to support this from a recent study in which 61 university undergraduate students were asked to sound out 51 of the most common, that is most frequently occurring, single- and multi-letter graphemes in isolation. Participants, on average, were able to correctly read less than 80% of the graphemes (*M* = 40.38, *SD* = 5.62).

Another possibility is that when children are taught GPCs explicitly, they associate single graphemes with their phonemes in the same way as they associate frequently occurring words with their pronunciation (including single- and two-letter words like I, a, oh, or). In other words, like familiar words, graphemes may have lexical representations in the orthographic lexicon. With increasing reading experience, this explicit lexical knowledge of GPCs is no longer required or reinforced and may become inaccessible for many adults. We hypothesise that this lexical knowledge is independent from the GPC mapping process used to read aloud nonwords. Clearly, however, the two types of information are closely related and it would be expected that, in general, they would be acquired in parallel. Nevertheless, this account predicts that it is possible for accuracy of reading of a grapheme in nonwords to dissociate from accuracy of reading that grapheme in isolation. This would predict variability in responses – as is the case here – the children were not at floor in their grapheme reading in nonwords. In addition to these considerations, there are models of reading that can offer a theoretical explanation for our results, including connectionist computational models of word reading. In essence, connectionist models are computer programs that simulate the sub-skills involved in reading and consist of large networks of simple neuron-like processing elements (units). Two examples of such models are the Parallel Distributed Processing (PDP) model (Plaut, McClelland, Seidenberg, & Patterson, 1996) and the Connectionist Dual-Process plus (CDP+) model (Perry, Ziegler, & Zorzi, 2007). In both of these models, grapheme to phoneme translation is complex, characterised as statistical and having a many-to-many relationship in that “each output phoneme may be determined by more than one of the input graphemes, and individual graphemes may contribute to the activation of more than one output phoneme” (Pritchard et al., 2012, p. 1270). It is in this complexity of grapheme to phoneme translation that the possibility arises for a multi-letter grapheme to be correctly read in nonwords, while incorrectly read in isolation. That is, the activation of an output phoneme in the context of a nonword is the result of the weighted activation from all the graphemes in the nonwords and not just a single grapheme, as is the case when reading graphemes in isolation. Connectionist computational models such as the PDP and CDP+ models may therefore provide a theoretical account for the dissociation between the accuracy of reading of a grapheme in nonwords and the accuracy of reading that grapheme in isolation. However, we stress that this would require explicit simulation before any further generalizations could be drawn.

Overall, it seems to be possible to correctly read multi-letter graphemes in the context of nonwords despite not being able to produce these in isolation. We offered two possible explanations for this: one in terms of grapheme reading in isolation being a task that may be performed using a different mechanism to that used to map graphemes onto phonemes in nonword reading, and the second in terms of the complex mechanisms of connectionist models of word reading.

Question 2: Do children with phonological dyslexia have difficulties with grapheme parsing or phoneme blending as well as poor GPC knowledge?

The two children in this study were both poor nonword readers. According to a dual-route model such as that shown in Figure 2, nonword reading can be poor for a number of reasons: poor knowledge of GPCs, poor ability to parse letter-strings into graphemes, or poor phoneme blending. Combinations of these impairments are also possible reasons for poor nonword reading. Most research today has focused on poor knowledge of GPCs. Indeed, both children in this study knew fewer GPCs than their peers. Neither of them had significant problems in blending sounds to form words. However, one of our two participants was particularly poor at parsing letter strings. This finding confirms that nonword reading can be associated with more than one deficit along the non-lexical route.

Conclusions

To our knowledge, this study is the first to investigate in detail the relationship between two non-lexical reading sub-skills: grapheme parsing and GPC knowledge. We aimed to address two questions. First, whether grapheme parsing and GPC knowledge were independent processes. The answer here is yes: There is clear evidence that grapheme parsing can be achieved without GPC knowledge. In addition, we have reported preliminary evidence that graphemes can be read successfully in isolation and in nonwords even when parsing of that grapheme is impaired. If this result is found to be replicable, this could be taken as evidence against an architecture like that of the dual-route model where GPC knowledge can only be applied after grapheme parsing has been achieved. Alternatively, incorrect grapheme parsing attempts may lead to phonologically illegal sequences, which are rejected by the phonological output system, triggering a re-parse.

The second aim was to address two previously untested predictions of the dual-route theory regarding non-lexical reading. Namely, that impaired GPC knowledge will result in impaired nonword reading. This was tested by asking children to provide the sound of selected graphemes in isolation and to read the same graphemes in the context of nonwords. We found evidence suggesting that grapheme sounding in isolation may be performed using a different mechanism to that used to map graphemes onto phonemes in nonword reading. Dual-route theory also predicts that children with poor nonword reading (i.e., phonological dyslexia) can have grapheme parsing or phoneme blending problems in addition to poor GPC knowledge. In this study, we found that one of our children with phonological dyslexia demonstrate impaired grapheme parsing in addition to poor GPC knowledge.

Considered together, the findings of this study support the fractionation of non-lexical processes in developmental dyslexia, and the idea that non-lexical reading comprises a grapheme parsing component that is independent to GPC knowledge. Future research should replicate the current study since it is the first to empirically test the relationship between grapheme parsing and GPC knowledge. Future studies might also consider including both accuracy and latency measures for nonword reading and it would also be helpful to include more target GPCs (including multi-letter consonants), to both clarify some of the issues raised in the current study and extend its generalisability. Finally, while the results of this study has theoretical implications, it also has implications for remedial or intervention programs. Namely, effective programs should to teach grapheme parsing and GPC knowledge as separate skills rather than assume that grapheme parsing will develop simply as a function of the development of GPC knowledge. We note that GPC knowledge is often taught concurrently with blending skills, beginning with simple one-letter graphemes before moving on to multi-letter graphemes. However, it is often not intuitive to children with dyslexia how to identify multi-letter graphemes and how to correctly blend their associated phonemes into words. Remedial programs that use explicit instruction in these skills would benefit these children.

References

Adams, C., Cooke, R., Crutchley, A., Hesketh, A., & Reeves, D. (2001). Assessment of comprehension and expression 6-11 (ACE6-11). Windsor, UK: Nelson.

Beauvois, M. F., & Derouesné, J. (1979). Phonological dyslexia: Three dissociations. *Journal of Neurology, Neurosurgery & Psychiatry*, *42*(12), 1115–1124.

Berndt, R., & Mitchum, C. (1994). Approaches to the rehabilitation of "phonological assembly": Elaborating the model of nonlexical reading. In G.W. Humphreys & M.J. Riddoch (Eds.), *Cognitive neuropsychology and cognitive rehabilitation* (pp. 503-526). Hove, UK: Erlbaum.

Berndt, R., Haendiges, A., Mitchum., C., & Wayland, S. (1996). An investigation of nonlexical reading impairments. *Cognitive Neuropsychology, 13*(6), 763-801. doi:10.1080/026432996381809

Brunsdon, R. K., Hannan, T. J., Nickels, L., & Coltheart, M. (2002). Successful treatment of sublexical reading deficits in a child with dyslexia of the mixed type. *Neuropsychological Rehabilitation*, *12*(3), 199-229. doi:10.1080/09602010244000048

Cassar, M., & Treiman, R. (1997). The beginnings of orthographic knowledge: Children's knowledge of double letters in words. *Journal of Educational Psychology*, *89*(4), 631-644.

Castles, A., Coltheart, M., Larsen, L., Jones, P., Saunders, S., & McArthur, G. (2009). Assessing the basic components of reading: A revision of the Castles and Coltheart test with new norms. *Australian Journal of Learning Difficulties*, *14*(1), 67-88. doi:10.1080/19404150902783435

Coltheart, M. (1985). Cognitive neuropsychology and the study of reading. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 3-37). Hillsdale, NJ: Erlbaum.

Coltheart, M. (2006). Dual route and connectionist models of reading: An overview. *London Review of Education*, *4*(1), 5-17. doi:10.1080/13603110600574322

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: a dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, *108*(1), 204-256. doi:10.1037/0033-295X.108.1.204

Crawford, J. R., & Garthwaite, P. H. (2002). Investigation of the single case in neuropsychology: confidence limits on the abnormality of test scores and test score differences. *Neuropsychologia*, *40*(8), 1196-1208. doi:10.1016/S0028-3932(01)00224-X

Crawford, J. R., and Garthwaite, P. H. (2005). Testing for suspected impairments and dissociations in single-case studies in neuropsychology: evaluation of alternatives using Monte Carlo simulations and revised tests for dissociations. *Neuropsychology*, 19, 318–331. doi:10.1037/0894-4105.19.3.318

Derouesné, J., & Beauvois, M. F. (1985). The “phonemic” stage in the non-lexical reading process: Evidence from a case of phonological alexia. In K. E. Patterson, J. C. Marshall, & M. Coltheart (Eds.), *Surface dyslexia: Neuropsychological and cognitive studies of phonological reading* (pp. 399–458). London, England: Erlbaum.

Dunn, L. M., & Dunn, D. M. (2007). Peabody picture vocabulary test 4th Edition. Bloomington, MN: NCS Pearson.

Frederiksen, J. R., & Kroll, J. F. (1976). Spelling and sound: Approaches to the internal lexicon. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 361–379. doi:10.1037/0096-1523.2.3.361

Gilbert, J. K., Compton, D. L., & Kearns, D. M. (2011). Word and person effects on decoding accuracy: A new look at an old question. *Journal of Educational Psychology*, *103*(2), 489-507. doi:10.1037/a0023001

Goodall, W. C., & Phillips, W. A. (1995). Three routes from print to sound: Evidence from a case of acquired dyslexia. *Cognitive Neuropsychology*, *12*(2), 113-147. doi:10.1080/02643299508251993

Graham, S. (1980). Word recognition skills of learning disabled children and average students. *Reading Psychology, 2,* 23–33. doi:10.1080/0270271800020106

Jones, M. N., & Mewhort, D. J. (2004). Case-sensitive letter and bigram frequency counts from large-scale English corpora. *Behavior Research Methods, Instruments, & Computers, 36*(3), 388-396.

Kaufman, A., & Kaufman, N. (2004). Kaufman Brief Intelligence Test 2. Circle Pines, USA: AGS.

Korkman, M., Kirk, U., & Kemp, S. (1998). *NEPSY: A developmental neuropsychological assessment*. San Antonio, USA: Psychological Corporation.

Larsen, L., Kohnen, S., Nickels, L., Castles, A., & McArthur, G. (2013). The Letter-Sound Test (LeST): a reliable and valid comprehensive measure of grapheme-phoneme knowledge. *Australian Journal of Learning Difficulties*, *20*(2), 129-152. doi:10.1080/19404158.2015.1037323

Laxon, V., Gallagher, A., & Masterson, J. (2002). The effects of familiarity, orthographic neighbourhood density, letter-length and graphemic complexity on children's reading accuracy. *British Journal of Psychology, 93*(2), 269-287. doi:10.1348/000712602162580

Marinus, E., Kohnen, S., & McArthur, G. (2013). Australian comparison data for the test of word reading efficiency. *Australian Journal of Learning Difficulties, 18*(2), 199–212. doi:10.1080/19404158.2013.852981

Mitchum, C. C., & Berndt, R. S. (1991). Diagnosis and treatment of the non-lexical route in acquired dyslexia: An illustration of the cognitive neuropsychological approach. *Journal of Neurolinguistics, 6*(2), 103-137. doi:10.1016/0911-6044(91)90003-2

Newcombe, F., & Marshall, J. C. (1984). Varieties of acquired dyslexia: A linguistic approach. In *Seminars in Neurology 4*(2), 181-195.

Newcombe, F., & Marshall, J. C. (1985). Reading and writing by letter sounds. In K.E. Patterson & J.C. Marshall (Eds.), *Surface dyslexia: Neuropsychological studies and cognitive studies of phonological reading.* Hove, England: Erlbaum.

Patterson, K. & Marcel, A. (1992). PHONOLOGICAL alexia or phonological ALEXIA? In J. Alegria & D. Holender (Eds.), *Analytic approaches to human cognition* (pp. 259-274). Amsterdam, Netherlands: North Holland.

Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: The CDP+ model of reading aloud. *Psychological Review, 114,* 273–315. doi:10.1037/0033295X.114.2.273

Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review, 103*(1), 56-115. doi:10.1037/0033-295X.103.1.56

Pritchard, S. C., Coltheart, M., Palethorpe, S., & Castles, A. (2012). Nonword reading: Comparing dual-route cascaded and connectionist dual-process models with human data. *Journal of Experimental Psychology: Human Perception and Performance, 38*(5), 1268-1288. doi:10.1037/a0026703

Share, D. L. (1995). Phonological recoding and self-teaching: sine qua non of reading acquisition. *Cognition, 55*(2), 151-218. doi:10.1016/0010-0277(94)00645-2

Share, D. L. (2008). Orthographic learning, phonological recoding, and self-teaching. In R.V. Kail (Ed.), *Advances in child development and behavior* (Vol. 36, pp. 31-82): New York, NY: Elsevier.

Stuart, M., & Stainthorp, R. (2016). *Reading development and teaching*. London, England: Sage

Temple, C. M. (1985). Surface Dyslexia: Variation within a syndrome. In K. Patterson, J.C. Marshall, & M. Coltheart (Eds.), *Surface dyslexia.* (pp. 269-288). Hillsdale, NJ: Erlbaum.

Temple, C. M., & Marshall, J. C. (1983). A case study of developmental phonological dyslexia. *British Journal of Psychology, 74*(4), 517-533. doi:10.1111/j.2044-8295.1983.tb01883.x

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). *Test of word reading efficiency.* Austin, TX: ProEd.

Wagner, R. K., Torgesen, J. K., & Rashotte, C.A. (1999). *Comprehensive Test of Phonological Processing (CTOPP)*. Austin, TX: ProEd.

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children* (4th ed.). San Antonio, TX: Psychological Corporation.

Ziegler J. C., Goswami U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131*, 3–29. doi:10.1037/0033-2909.131.1.3

Zorzi, M., Houghton, G., & Butterworth, B. (1998). Two routes or one in reading aloud? A connectionist dual-process model. *Journal of Experimental Psychology: Human Perception and Performance, 24*(4), 1131-1161. doi:10.1037/0096-1523.24.4.1131

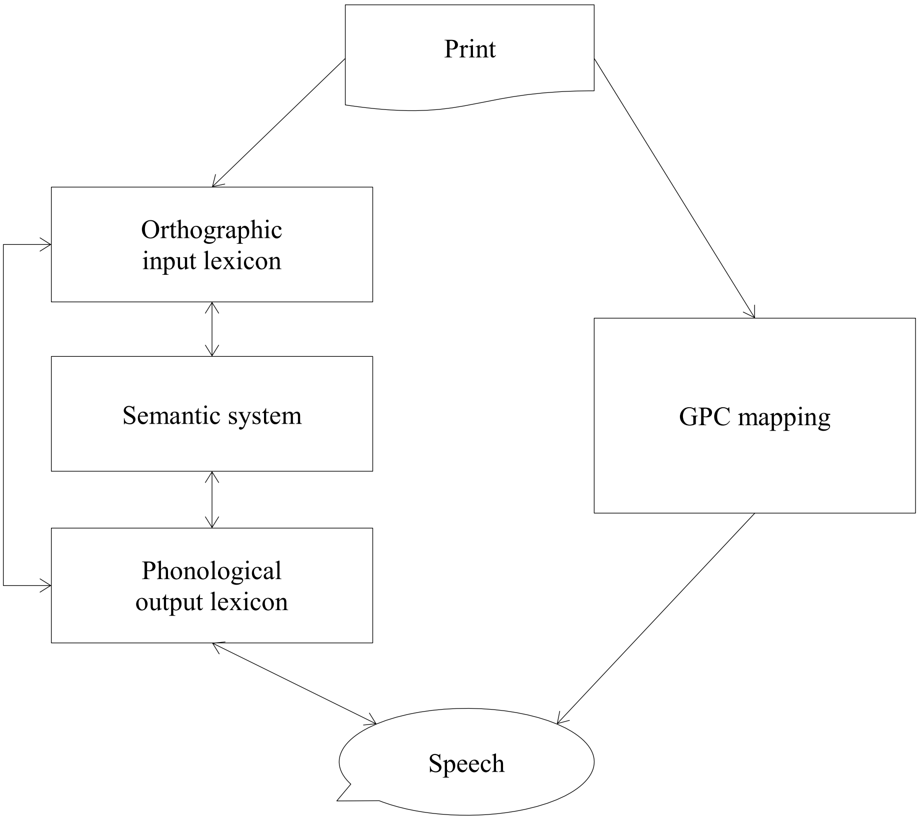

Figure 1. Schematic representation of the dual-route framework. (Adapted from Coltheart, 2006).

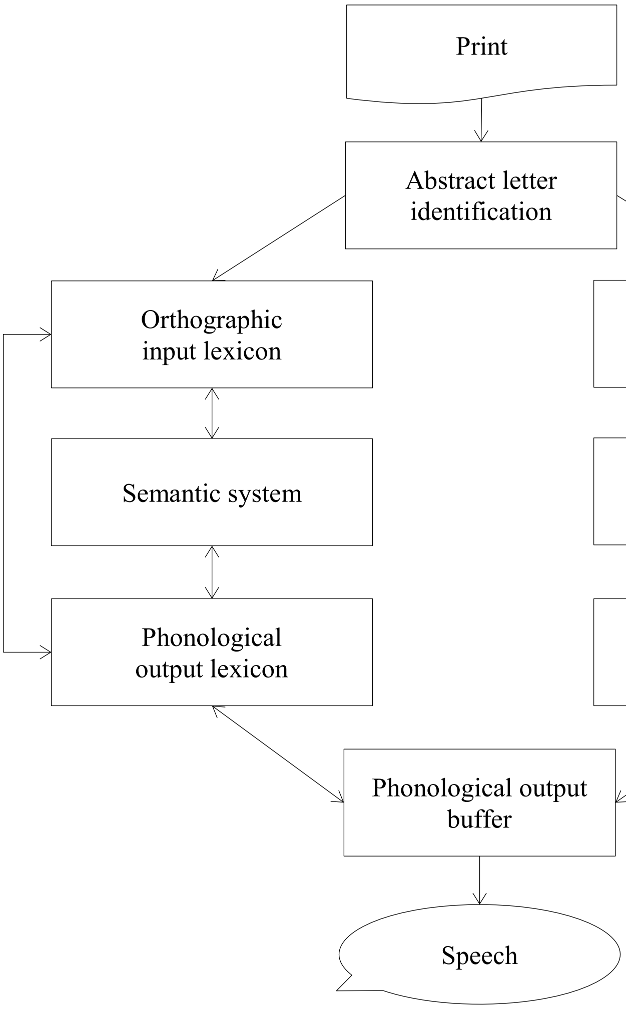

Figure 2. Schematic representation of a dual-route model with separate parsing and blending components. (Adapted from Mitchum & Berndt, 1991).

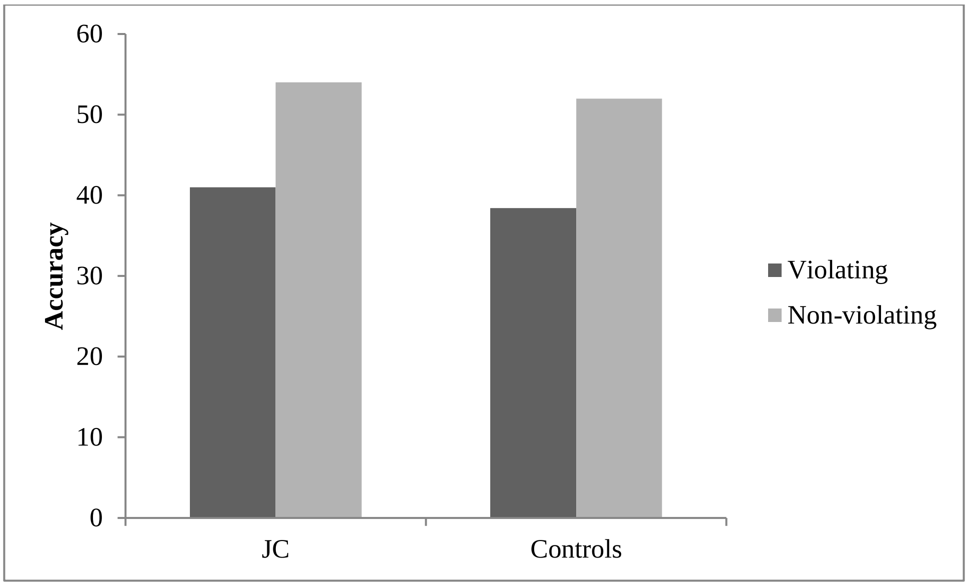

Figure 3. Accuracy (/56) on the embedded word task across *known* and *unknown* GPCs for violating and non-violating conditions. JC’s performance in the violating condition relative to the non-violating condition was similar to control performance.

Table 1

Background Assessments for JC and JW

	JC (10 years 6 mths)		JW (11 years 3 mths)	
	Raw score	%ile	Raw score	%ile
Reading assessments				
CC2 nonwords (Castles et al., 2009)	10	2	16	5
CC2 irregular words (Castles et al., 2009)	23	42	22	21
Non-lexical assessments				
LeST GPC knowledge (Larsen et al., 2013)[a]	38	22	36	13
Phoneme blending (unpublished test)[b]	13/21	t = -1.20, p = .28	14/28	t = -0.66, p = .56
CTOPP segmenting (Wagner et al., 1999)	7	25	6	16
WISC-IV digit-span forward (Wechsler, 2003)	14	23	6	5
WISC-IV digit-span backward (Wechsler, 2003)	7	25	6	25
NEPSY nonword repetition (Kork et al., 1998)	--	--	35	50
Cognitive and language assessments				
K-BIT 2 - Matrices (Kaufman & Kaufman, 2004)	37	90	34	66
ACE6-11 expressive (Adams et al., 2001)	20	63	17	25
PPVT-IV receptive (Dunn & Dunn, 2007)	145	32	166	61

Note. Performance between the 16th and 84th percentile is within one standard deviation of the normative sample and considered to be in the normal range.

[a] The LeST has normative data from Kindergarten to Grade 3. JW performed within the normal range for Grade 3, but below the average of his control group. JC performed below the normal range for Grade 3. [b]This is the only unstandardised assessment and Crawford and Garthwaite's *t*-statistic was used to determine whether phoneme blending was significantly different from the control group.

Table 2

Individual Known and Unknown Vowel Multi-letter GPCs

GPC		**JC**	**JW**
Known	GPC1	OI-/ɔɪ/	OI-/ɔɪ/
	GPC2	AY-/eɪ/	OA-/əʊ/
Unknown	GPC1	OA-/əʊ/	AI-/eɪ/
	GPC2	EA-/iː/	EA-/iː/

Table 3

Summary of Experimental Assessment Measures (raw scores) and Comparison of JC and JW's Performance with that of Controls Matched on Number of School-terms Completed using Modified t-statistics (Crawford & Garthwaite, 2002)

	JC			Controls (***n*** = 7)		JW			Controls (***n*** = 4)	
	Raw score (/13)	*t*	*p*	***M***	***SD***	Raw score (/13)	*t*	*p*	***M***	***SD***
Parsing nonwords ('unknown' GPCs)										
GPC1	13[a]	0	1	13	0.01	8	-0.80	.48	11	3.37
GPC2	12	-2.12	.08	12.86	0.38	11	-0.15	.89	11.50	3
Parsing nonwords ('known' GPCs)										
GPC1	13	0.55	.60	12.71	0.49	6	-0.81	.48	10.50	5
GPC2	13[a]	0	1	13	0.01	6[ab]	-62.61	**<.001**	13	0.10
Nonword reading ('unknown' GPCs)										
GPC1	5	-3.63	**.01**	11.86	1.77	5	-13.86	**<.001**	12.75	0.50
GPC2	3	-6.14	**<.001**	11.86	1.35	9	-1.94	.15	12.25	1.50
Nonword reading ('known' GPCs)										
GPC1	4	-21.81	**<.001**	12.86	0.38	5	-1.94	.15	11.50	3
GPC2	13[a]	0	1	13	0.01	13[a]	0	1	13	0.01

Note: Two-tailed *t*-statistics are reported with significant results shown in boldface. [a]Estimated *SD* = 0.01 as mean performance at ceiling. [b]A binominal test shows that JW is at chance level, *z* = 0.277.

Table 4

Summary of Embedded Word Parsing Task Measure (raw scores) and Comparison of JC's Performance with that of Controls using Revised Standardized Difference Test (RSDT) (Crawford and Garthwaite, 2005)

	JC				Controls (***n*** = 7)	
	Raw score (/14)		*t*	*p*	***M*** (***SD***)	
	Viol.	Non-viol.			Viol.	Non-viol.
'unknown' GPCs						
GPC1	11	14	0.05	.95	8.43 (1.90)	12.57 (1.13)
GPC2	10	14	0.88	.41	11 (1.41)	13.71 (0.49)
'known' GPCs						
GPC1	9	12	1.64	.15	7.86 (2.34)	13.14 (0.90)
GPC2	11	14	0.55	.60	10.43 (1.99)	12.43 (1.13)
All GPCs	41	54	0.11	.92	38.43 (3.69)	52 (2.31)

Note: Two-tailed *t*-statistics are reported.