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When 'slime' becomes 'smile': Developmental letter position dyslexia in English[✻]

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We report the first three cases of selective developmental letter position dyslexia in English. Although the parents and teachers of the children were concerned about these children's reading, standard tests did not reveal their deficit. It was only when the appropriate target words were presented, in this case, migratable words, that their letter position dyslexia was detected. Whereas previous research has described cases with acquired and developmental forms of letter position dyslexia in Hebrew and Arabic readers, this is the first report of this type of reading disorder in English. The cardinal symptom of letter position dyslexia is the migration of letters within the word (reading *slime* as 'smile'; *pirates* as 'parties'). These migration errors occur in reading aloud as well as in tasks of silent reading. This study provides further evidence that migration errors emerge at the level of early visual-orthographic analysis, in the letter position encoding function. Alternative explanations for the occurrence of migration errors such as poor phonological processing or a deficit in the orthographic input lexicon are ruled out.

1. Introduction

Teachers who work with children with reading difficulties report that errors such as reading *form* as 'from', or *slime* as 'smile' are common. These errors where letters swap position are often cited in the popular literature as the hallmark sign of dyslexia. Yet, to our knowledge, there is no thorough documentation of a selective letter position coding deficit in English developmental dyslexia. Such a difficulty, however, does exist – at least in other languages. Friedmann and Rahamim (2007) were the first to describe this developmental deficit in detail. They examined the reading performance of 11 Hebrew-speaking participants with a

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selective developmental deficit for the encoding of letter positions within words (see also Friedmann, Dotan, & Rahamim, 2010; Friedmann & Gvion, 2005; Friedmann & Rahamim, in press). In later work, Friedmann and Haddad-Hanna (2012, in press) described a very similar deficit in Arabic readers. It may be that differences between languages impact on the likelihood of occurrence of migration errors; and English may be less prone to migration than Hebrew and Arabic. For example, Hebrew's rich morphological structure and its underrepresentation of vowels make it possible to form other existing words by simply changing letters in the word. Whereas differences may exist between orthographies with respect to the *detectability* of letter position errors, if reading in English requires similar abstract processes to Hebrew and Arabic, then problems with letter position coding should be observable in English-reading children as well.

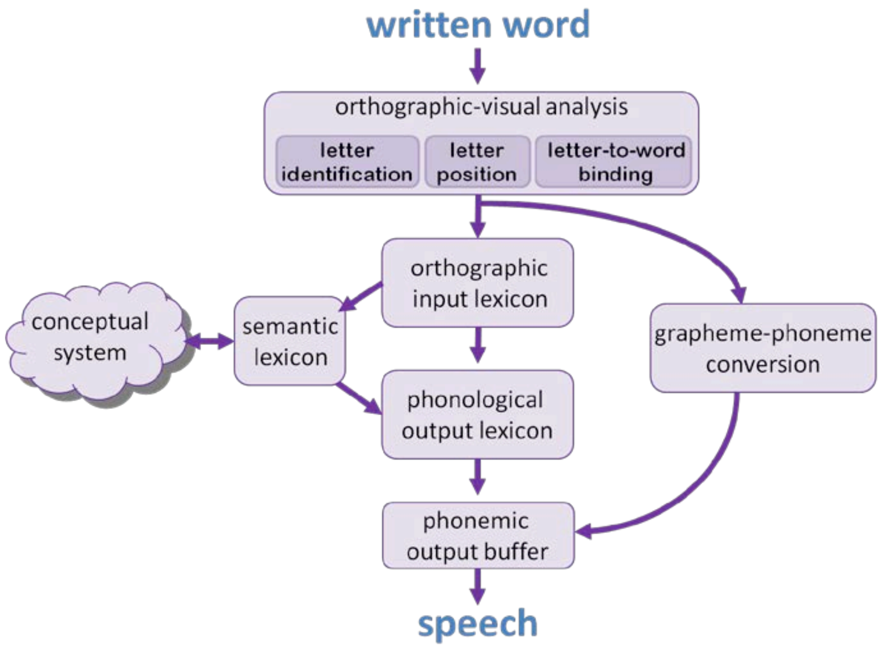

Figure 1. A dual route model of reading

According to the cognitive model of reading outlined in Figure 1 (e.g., Friedmann & Rahamim, 2007), the first stage of translating print to sound and meaning is a stage of orthographic-visual analysis. Orthographic-visual analysis consists of three functions: abstract letter identification, the encoding of relative letter positions within words, and letter-to-word binding. The letter-to-word binding process associates or 'binds' letters to the word in which they occur. For example, when reading the word pair *dark part* the reader needs to 'bind' the *d, a, r*, and *k* to the first word and the *p, a, r*, and *t* to the second word, otherwise, 'park dart' may be read instead of 'dark part'. After these initial computations, written input is processed via three routes: (1) the lexical route (orthographic input lexicon to phonological output lexicon), (2) the lexical-semantic route (orthographic input lexicon to the semantic lexicon and the conceptual system) or (3) the nonlexical route (conversion of graphemes into phonemes). Under normal circumstances the lexical and lexical-semantic routes can successfully read any known letter string (i.e., words in the child's reading vocabulary), but will fail for novel letter strings (e.g., nonwords like *furp, blerk*). In contrast, the nonlexical route can successfully read any novel string, and any string with regular spelling-sound correspondences but will fail for irregularly pronounced words (e.g., *listen, door, walk*). The subsequent phonological output stages involve assembling of phonemes in the phonemic output buffer and holding them activated until the production of the word.

Selective difficulties in acquiring most of the reading components (i.e., boxes and arrows) in Figure 1 have been reported for English-reading children. For example, Brunsdon, Coltheart, and Nickels (2006) reported the intriguing case of a boy with a deficit in acquiring letter identities. Difficulties that affect the lexical route (also known as surface dyslexia) have been described by several research teams[1] (e.g., Broom & Doctor, 1995; Castles & Coltheart, 1993; Temple, 1997) and selective difficulties in the nonlexical route resulting from impaired grapheme-to-phoneme conversion or from a phonemic output buffer impairment are also thought to be relatively common (phonological dyslexia: e.g., Castles & Coltheart, 1993; Snowling, 1989; Temple, 1983). Castles, Crichton, and Prior (2010) documented two cases of hyperlexia where the lexical-semantic link appears to be impaired. However, there are two components of the model that are notable exceptions, in that they currently have no reports of selective impairments in English: letter position-encoding (developmental or acquired) and developmental letter-to-word-binding[2]. In this research, we fill one of these gaps by describing what we believe are the first developmental cases of English letter position dyslexia to be reported in the literature.

The Hebrew and Arabic studies have established that the hallmark feature of letter position dyslexia is that the reader makes a disproportionate number of letter 'migration' errors (Friedmann, Dotan, & Rahamim, 2010; Friedmann & Gvion, 2001, 2005; Friedmann & Haddad-Hanna, 2012, in press; Friedmann & Rahamim, 2007, in press). These errors typically stem from a transposition of letters within a word that result in another word – an anagram of the target word (e.g., *slime* read as 'smile'; *warp* read as 'wrap'). These migration errors occur

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[1] Note, however, that there are currently no cases reported with selective deficits to single components along the lexical route in English (for Hebrew, see Friedmann and Lukov (2008)).
[2] Rayner et al. (1989) described an individual who showed one of the symptoms associated with impaired letter-to-word binding, namely, better reading of single words than texts. However, as their description includes only reading speed data and no information on error types, it is hard to be confident regarding the precise localisation of the functional impairment.

mainly when the migration creates an existing word (in what has been termed "migratable words"). It was also established that most errors occur with letters in the middle positions of the word.

In addition, when letter position dyslexia is selective, children make no errors of letter identity (e.g., *form* as 'farm', *form* as 'fork'), nor do they make more between-word letter migrations (e.g., *dark part* -> park dart) than expected for their age. The fact that such a selective impairment of letter position encoding can be found suggests that two of the three processes in the orthographic-visual analyser – letter identification and letter-to-word binding – are intact in children with letter position dyslexia. It is the processes associated with letter-position encoding in the orthographic-visual analyser that appear to be specifically impaired.

Beyond the orthographic-visual analyser, there are at least two other processing components that could also cause migration errors in reading aloud. For example, migration errors could occur due to a difficulty in processing phonological output (i.e., the phonemic output buffer). Hence, instead of transposition of letters, it may be the phonemes whose order is being swapped. The data of Friedmann and Rahamim (2007) argue against this, however. They found that children with letter position dyslexia (1) could repeat words and nonwords without error, (2) had no difficulties in phoneme awareness tasks that draw heavily on the phonological output buffer, and (3) had error-patterns in their silent reading – which required no phonological output - that were similar to their reading aloud. A second alternative explanation for the generation of migration errors is that they are a form of "lexical guessing" due to an impoverished lexicon. That is, migration errors occur because an orthographically related word is activated in the orthographic lexicon instead of the target word. Sometimes, the orthographically related word will be the word's migration partner. If this were true, a migration error (e.g., *blows* as 'bowls') would be as likely to occur as another error that is a close orthographic match to the input representation (e.g., *blows* as 'brows'). The fact that the vast majority of errors made by letter position dyslexics are migration errors (and not other close orthographic matches) supports the interpretation that migration errors are not just a form of general lexical guessing.

Considered together, the existing evidence suggests that the source of letter position dyslexia is impaired letter position processing in the orthographic-visual analyser. What then is the actual deficit in processing letter positions? Two possibilities are discussed by Friedmann and Rahamim (2007). Letter positions may be coded incorrectly. For example, when asked to read *slime*, the letter 'l' is coded in position 4 rather than 2 and 'm' is coded in position 2 rather than 4. Alternatively, the specification of the positions for each letter may be imprecise (e.g., 'I' and 'm' are all somewhere between positions 2 and 4). The results of Friedmann and Rahamim's data were more consistent with the underspecification account because low frequency words (e.g., *slime*) were more likely to attract migration errors (i.e., being read as 'smile') than their higher frequency anagram partners (e.g., *smile* read as 'slime'). In the case of *slime* and *smile*, this suggests that the low frequency word (*slime*), for which the order of the middle letters is underspecified, activates two words in the lexicon (*smile, slime*), and the higher frequency word (*smile*) wins over its lower frequency neighbour (*slime*). Frequency should not be a significant predictor of migration errors if letter positions were incorrect rather than underspecified. If letter positions were simply encoded in the wrong way, then the word that matches the miscoded positions should be activated regardless of whether it is more frequent or not.

It seems that, at least in Hebrew, the underspecification of letter position coding does not affect all letter position to the same degree: Encoding of initial and final positions (i.e., the exterior letters) is more resilient. This is shown by the fact that migration of middle letters in words occurred more frequently than migration of exterior letters (e.g., *form* – *from* vs. *lots* – *lost*; Friedmann & Rahamim, 2007). Friedmann and Rahamim (2007) also found that migration errors were more likely to occur for words with adjacent (e.g., *trail* – *trial*) than non-adjacent (e.g., *smile* – *slime*) migration potential. This finding is in line with other research on the transposition of letters in adult skilled readers (e.g., Perea, Duñabeitaia, & Carreiras, 2008).

In sum, work in Hebrew and Arabic suggests that letter position dyslexia stems from a selective impairment in the letter position component of the orthographic-visual analyser in the reading system. This impairment appears to reflect underspecified coding of letter positions in written letter strings.

In this study, we investigated the following questions: Does selective letter position dyslexia exist in English? If so, which component(s) of the reading system are responsible for the production of migration errors? Finally, what characteristics of words impact on the likelihood of a migration error occurring?

2. Method

This project had ethics approval through Macquarie University. The participants and their parents gave verbal and written consent to be involved in our research.

2.1 Participants

Our participants with developmental letter position dyslexia were three 8 year old boys who were in Grade 3 (which equates to four years of formal schooling). All three children were poor spellers (for nonwords: EC, or irregular words: EL, or for both: NN).

Our first participant, EC, attended a government school in suburban Sydney. EC's mother contacted us because she was concerned about his spelling. She also told us that EC's teachers thought his reading was not as good as she perceived it to be. EC had previous diagnoses of delayed reading but a very recent assessment by the school councillor revealed no concerning results. EC comes from a family with reading difficulties, both his parents were slow to learn to read and EC's mother reported that even today her error rates are high when she is tired. One of EC's siblings had not yet commenced school, and the other sibling's reading was developing without difficulties. EC's vision and hearing had been tested just before the commencement of this study and found to be normal. During the course of this study, EC was assessed by a developmental psychologist and diagnosed with attention deficit disorder (ADD).

Our second participant, NN, was a student in a mainstream suburban private school. He was referred to the authors because of concerns regarding his literacy skills. NN's mother reported that NN's teachers were worried about a lack of progress in his reading. However, the teachers could not identify a reading difficulty using their standard battery of tests. NN had had some school-based reading intervention when he was in Grade 1. He received on-going help with his homework from a private tutor. One of NN's siblings had been diagnosed with spelling difficulties. While he had no formal diagnosis of any developmental difficulties (including ADD/ADHD), NN was very easily distracted during the testing sessions and found it challenging to stay in his chair. NN's vision and hearing had been tested and found to be normal. He was seeing an Occupational Therapist to help with poor fine motor skills and poor "eye coordination" (which turned out to be letter position dyslexia).

Our third participant, EL, attended a mainstream suburban government school. He was referred to the authors because of concerns regarding his spelling. EL was reported to have been slow in learning to read and was in the lowest reading group at the beginning of his school career. According to his mother, EL had made steady progress since then and there were no concerns regarding his reading at the time of this study (by his mother or the teachers). EL's hearing was tested as normal. However, he has congenital nystagmus (i.e., a very noticeable involuntary horizontal eye movement). There were no diagnoses of developmental delay, AD(H)D nor SLI. Neither EL's parents nor his younger sister had literacy difficulties.

2.2 Procedure

The first author assessed EC on four occasions, spread out over two months. NN was assessed by a research assistant and the first author three times over four weeks. EL was assessed by a research assistant and the first author four times over three months. The testing sessions were carried out at Macquarie University. Each session lasted between an hour and two hours. The first author also tested six control children at their school. The control children completed all tests in a single 1-hour session.

3. Results

3.1 Standard background assessment

We assessed lexical reading by asking the children to read aloud 40 single regular and 40 single irregular words (Castles & Coltheart Reading Test (CC2): Castles et al., 2009), and 60 single regular and irregular words (between basal and stopping rule) (WIAT-II word reading: The Psychological Corporation, 2002). It is noteworthy that the words in these tests are not controlled for migratability. We also assessed the participants' nonlexical reading skills by asking them to read aloud a list of 40 nonwords from the CC2 (Castles et al., 2009) and 54 nonwords from the Martin and Pratt Nonword Reading Test (Martin & Pratt, 2001), (EC reached the stopping rule after reading 42 nonwords, NN after 32 nonwords, and EL after 39 nonwords). The Martin and Pratt nonword reading test contains no items with the potential to create a word by transposing middle letters. The CC2 nonword list contains one item where middle migration results in a word response (*crat* -> cart).

Text reading accuracy and comprehension were assessed using the Neale analysis of reading ability 3rd edition (Neale, 1999). In the Neale, children are asked to read several stories aloud. The stories are passages of text with increasing length and difficulty. (EC read 5 texts before reaching the stopping rule, NN read 4 and EL read 6). At the end of each story, the tester asks the children between four and eight comprehension questions. The text is covered so that the children cannot refer back to the text when answering the questions.

Using the tests above, we compared the participants' performance against large normative samples. As is common in this field of research and in clinical practice, performance within one standard deviation of the norm sample was viewed as a normal performance (i.e., a performance between the 16th and 84th percentile).

Table 1 provides an overview of the participants' reading abilities using standard measures of word (CC2, WIAT) and nonword reading (CC2, Martin & Pratt). On these standard measures, the children showed a normal reading performance. Single word reading was only impaired when reading migratable words, as will be reported in detail in the next section.

Both EC and NN scored below average for text reading accuracy. Text reading comprehension was in the low average to average range. When listening back to the recordings of the children's text reading without also looking at the text it was relatively hard to follow the contents of what was being read as the texts became longer and more difficult. EC, for example, would sometimes add function words[3] (e.g., *to, a, the, and*) or leave them out. EC and NN made word substitutions (e.g., *spring* as 'springs'; *taking* as 'talking') and also some nonword responses (e.g., *tangling* as 'taggling'). Some of these errors (especially the omission of letters that occur several times in a word) have been reported for Hebrew-reading children with letter-position dyslexia (Friedmann & Rahamim, 2007). EL's text reading accuracy and comprehension were in the normal range.

Table 1. EC, NN and EL's reading– standard tests without migratable words

Test	**EC**		**NN**		**EL**	
	Raw Score	%ile	Raw Score	%ile	Raw Score	%ile
Word Reading						
CC2 irregular words (Castles et al., 2009)	15	50[a]	16	29	17	46
CC2 regular words (Castles et al., 2009)	30	56	31	33	31	43
WIAT word reading (The Psychological Corporation, 2002)	97	58	87	32	101	68
Nonword Reading						
CC2 nonwords (Castles et al., 2009)	16	39[a]	18	28	16	29
Martin & Pratt nonwords (Martin & Pratt, 2001)	28	70	21	34	21	34
Text Reading						
Neale accuracy (Neale, 1999)	26	5[b]	28	7[b]	46	37
Neale comprehension (Neale, 1999)	13	17	14	23	22	59

Notes. [a] EC is a young 3rd grader, hence, when using age-based norms, his scores will translate to a higher %ile score than NN and EL's; we used grade-based norms where available.
[b] Represents a score below the normal range (defined as more than one SD below the mean, see text)

[3] Note, however, that there was no particular difficulty in reading the function words in the word lists.

3.2 Reading aloud migratable words

Studies of letter position dyslexia have indicated that individuals with this dyslexia make migration errors predominantly in migratable words, whereas they make very few errors on other words. Therefore, rather than indicating that our participants are normal readers, their average-range performance in reading single words and nonwords may merely indicate that the standard tests we used were not sensitive for detection of letter position dyslexia, as they did not include migratable words. To test whether the participants have letter position dyslexia, we assessed their reading aloud of a set of 60 migratable words (created from 30 pairs of a word and its migration counterpart; e.g., *slime* – *smile*). All but four of the words appeared in the children's printed word database (Masterson, Stuart, Dixon, & Lovejoy, 2010) either in the exact form presented to the children or in another morphological form. Their listing in the Children's Printed Word Database indicates that these words should be known to readers in primary school. The words were presented in two columns printed on two pages. A word and its migration counterpart were never presented on the same page. For example, if the word *pirates* appeared on the first page, the word *parties* would appear on a different page. The minimum distance between two word pair partners was 29 intervening words. We classified the errors the participants made into migration errors (e.g., reading *slime* as 'smile'), other, non-migration word errors (e.g., reading *slime* as 'slide'), and non-migration nonword responses (e.g., reading *slime* as 'plime'; note that there were no migrations of the word targets that resulted in nonword responses e.g., reading *slime* as 'silem'). Normative data exists for this word list so that we could compare the three participants to a sample of 66 readers in the same grade whose reading of nonwords and words was in the average range as assessed on the test of word reading efficiency (TOWRE, Torgesen, Wagner, & Rashotte, 1999).

The results, summarized in Table 2, indicated that the three participants had considerable difficulty in reading migratable words. EC and EL made about twice as many migration errors as the norm sample and NN made more than four times as many migration errors. The number of migration errors that EC, NN and EL produced (e.g., *slime* as 'smile') put them in the lowest 3% for their grade, and was significantly different to the norm samples' performance (EC: $t(65) = -1.6$, $p = .059$; NN: $t(65) = -6.3$, $p < .001$; EL: $t(65) = -2.1$, $p = .02$; using Crawford and Garthwaite's (2002) t-test to compare EC, NN and EL to the 66 control children).

When presented with migratable words, EC and EL read fluently and confidently as they did on the other word lists – but they made many migration errors. As with the other word lists, NN's reading was also more hesitant on the migratable words list. We did not observe frequent attempts to sound out words. In addition, the children did not seem aware of their migration errors. When reading the second half of the migratable words list, EC alerted the first author to the fact that 'I have already read a lot of these words. They are the same as on the other page.'

Table 2: Migratable words reading – results

N = 60 words	**EC**		**NN**		**EL**		**Controls** (*N*=66)	
	Raw score	%ile	Raw score	%ile	Raw score	%ile	Mean	SD
Correct responses	43	39	19	3	40	35	44.4	9.9
Migration errors	14	3	34	<1	16	1	7.3	4.2
Word errors	1	77	4	42	2	64	5.6	5.7
Nonword errors	2	41	3	26	2	41	2.6	2.3

In contrast to the large number of migration errors they made, EC, NN and EL showed similar rates of the two other error types to controls: the number of words read with non-migration errors as other words (e.g., *could* as 'cold'; EC: t = 0.80, *p* = .21; NN: t = 0.28, *p* = .39; EL: t = 0.63, *p* = .27) or nonwords (e.g., *cutlery* as 'cuttely'; EC: t = 0.26, *p* = .40; NN: t = -0.17, *p* = .43; EL: t= 0.26, *p* = .40). The vast majority of EC, NN and EL's reading errors were migrations (82%, 83% and 80% respectively). These results indicate that EC, NN and EL have a selective tendency to make migration errors when reading migratable words.

In sum, EC, NN and EL's reading of the list of migratable words showed a pattern that was not normal, although their reading of single words and single nonwords measured on some of the standard tests used to assess Australian children's reading was in the normal range (see Section 3.1). This selective deficit was also apparent in the fact that the children achieved normal scores on the CC2 and WIAT-II word lists but scored in the lowest 3rd percentile on the migratable words list. However, the words from the CC2, the WIAT and the list of migratable words differ in frequency and length. Hence, to provide a more rigorous comparison of error rates between the migratable words and the non-migratable words, we matched 20 regular non-migratable words from the CC2 to 20 regular words from the migratable words list[4] for frequency (mean log frequency = 1.3 for both item sets) and length

[4] Due to the stopping rules applied to the tests, it was impossible to match a sufficient number of irregular migratable and irregular non-migratable words.

(mean = 5.1 letters for both item sets). EC read correctly 80% of the non-migratable CC2 words but only 47% of the migratable words. This difference was significant (Fisher's exact test p = .015). NN read 83% of the non-migratable CC2 words correctly but only 33% of the matched migratable words. Again, the difference was significant (Fisher's exact test p < .001). Lastly, EL read 83% of the non-migratable CC2 words correctly compared to 60% of the matched migratable words, which was a significant difference (Fisher's exact test p = .049). These results show that EC, NN and EL are good readers of non-migratable words, and significantly worse at reading migratable words, and that they made more migration errors than children their age but not more non-migration errors. Importantly, it is clear that a difficulty in reading migratable words can be missed when only non-migratable words are administered in a reading test.

3.3 Assessing the locus of impairment

Having established that EC, NN and EL have a deficit in reading migratable words aloud, we administered a series of tasks that would help establish the source of these errors within the reading system. We first aimed to rule out an impairment at the phonological output stage as a source of the migration errors. If migration errors were a result of such an impairment, then they should not occur in silent reading tasks (like visual lexical decision), as silent reading tasks do not require spoken output. Moreover, migration errors should occur in spoken production tasks that do not involve reading. Hence, the first tasks we shall report involve silent reading and spoken production.

3.3.1 Silent reading tasks

Three silent reading tasks (details below) were administered to the participants. We used Crawford and Garthwaite's (2002) modified t-test to compare EC, NN, and EL against a control group. The controls were six children who studied in Grade 3 in a suburban Sydney school. We used the migratable words list as a screening instrument to select children from one Grade 3 class. Given that EC, NN and EL's reading is placed in the normal range for their age, we excluded Grade 3 children whose overall accuracy on the migratable words list indicated that they were poor readers (i.e., in the lowest 15%). Further, we matched the control children to the participants on the word errors and other errors made on the migratable words list. The six control children made an average of 3 migration errors, 2 word errors and 1 nonword error.

Table 3. Error rates for controls and dyslexics on silent reading tasks.

	EC			NN			EL			Controls	
	N	*t*	*p*	*N*	*t*	*p*	*N*	*t*	*p*	Mean	SD
<u>*Lexical decision (n=80)*</u>											
Migratable nonwords (*n*=20)	9	***5.84***	***.001***	7	***4.42***	***.003***	16	***10.83***	***<.001***	0.8	1.3
Non-migratable nonwords (*n*=20)	4	***3.06***	***.01***	3	***2.13***	***.04***	4	***3.06***	***.01***	0.7	1.0
Existing words (*n*=40)	5	-0.74	.25	7	0.0	.50	4	-1.11	.16	7	2.5
<u>*Definition (n=40)*</u>											
Migration errors	8	***2.13***	***.04***	11	***3.34***	***.01***	11	***3.34***	***.01***	2.7	2.3
Other errors	6	-0.48	.33	4	-1.12	.16	3	-1.44	.11	7.5	2.9

Note. Significant results (one-tailed) in bold italics.

Lexical decision. In this task we presented 80 written items to the participants and asked them to decide without reading the word aloud whether an item was a word or not. There was no time limit. Half of the stimuli (*n*=40) were existing words, the other half were nonwords. Twenty of the nonwords were migratable nonwords for which a migration of middle letters creates an existing word (e.g., *bron, fersh, snept*); the remaining 20 were non-migratable nonwords for which no middle migration would create a word (including 15 nonwords for which no possible middle migration would create an orthographically legal sequence (e.g., *norg, yarm, zompt*).

As Table 3 shows, EC, NN, and EL accepted significantly more migratable nonwords as words than the controls, indicating migration errors in silent reading. EC, NN and EL also made significantly more errors on the non-migratable nonwords. However, while the normal controls accepted similar amounts of migratable and non-migratable nonwords as words, EC, NN and EL accepted at least twice as many migratable nonwords than non-migratable nonwords. There was no difference in the number of errors on the existing words between the controls and the dyslexics.

Definitions. In the definitions task, we presented 40 written migratable words (created from 20 migratable words and their migration counterparts) and asked the participants to define each word without reading it aloud and without using the word in the definition[5]. The words were presented in split halves so that the children did not see both words in a pair on the same piece of paper. We classified the responses into definitions corresponding to accurate responses, migration errors (e.g., defining *diary* as "comes from a cow"), or other errors (mostly 'don't know' responses).

EC, NN, and EL produced significantly more migration errors than the control participants in the definition task (see Table 3). It is worth noting that Friedmann and Rahamim's participants made between 14% and 56% migration errors in the definition task. EC, NN and EL were in the middle of this range with 20%, 28% and 28% migration errors, respectively. There was no significant difference in the number of 'don't know/incorrect' responses ('other errors') between the controls and the dyslexic participants.

3.3.2 Spoken production tasks

Having established that migration errors occur also in reading tasks that do not require oral production, we continued to assess oral production using tasks that did not involve orthography: word and nonword repetition, and phonological awareness tasks. The participants were tested on the NEPSY nonword repetition test (Korkman, Kirk, & Kemp, 1998) which includes 13 nonwords that are 2-5 syllables, 4-17 phonemes long. All three children performed normally on this task, EC was in the 63rd percentile, NN in the 50th and EL in the 75th percentile. We further asked EC to repeat all of the words and nonwords that were used in the different reading tasks. He did not make a single migration error in these spoken repetition tasks either.

We tested the dyslexic participants' phonological awareness skills using three different tests: a phoneme deletion test (Elisions subtest, CTOPP, Wagner, Torgesen & Rashotte, 1999), a spoonerism test (PhAB, Frederickson, Frith, & Reason, 1997), and a phoneme segmentation test (QUIL, Dodd, Holm, Oerlemans, & McCormick, 1996). These tasks draw heavily on phonological output procedures. If the migration errors in reading stemmed from a problem with phonological processing, performance on the phonological awareness tasks should be impaired. As Table 4 shows, all three participants' scores were within the normal range (16th – 84th percentile) on all of the phonological awareness tests administered to them.

[5] The participants did not always follow these instructions. We reminded them to try and not read the words aloud or use them in the definitions.

Table 4: Percentile scores on Phonological Awareness tasks.

	Percentiles		
	EC	**NN**	**EL**
Phoneme Deletion (CTOPP Elisions)	25	25	75
Spoonerisms (PhAB)	68	32	40
Phoneme Segmentation (QUIL)	50	16	91

The results above show that the children's letter position encoding difficulties do not only occur in the reading aloud tasks but are also evident in tasks requiring no spoken response. This indicates that the problem is unlikely to be caused at the phonological output level. In addition, it is noteworthy that not every migration reading error could be caused at the phonological output stage, as illustrated by the following example: If the word *fits* is read as 'fist', this could be a result of difficulties with the encoding of letter positions. Alternatively, the letters could have been translated into the correct phonemes, but then the order of the phonemes may have been changed while the phonemes are held in the phonemic output buffer. However, there is no such ambiguity in the origin of a migration error when a word such as *cloud* is read as 'could', or *three* is read as 'there', because the word pronunciations contain different phonemes. Thus, in order to support our claim that the migration errors in our three cases were not due to phonological output impairments, we examined their error patterns in our stimuli. Two thirds of the 244 items in a long list of migratable words (more details in 3.4) were of the 'cloud-could' type and only one third of the 'fits-fist' type. Our participants showed no tendency to make more errors on the 'fits-fist' phonemic output buffer-type items (EC: Fisher's exact z = 0.28, p = .39, one-tailed; NN: Fisher exact z = 0.00 p = .50, one-tailed; EL: Fisher's exact z = -0.13, p = .55, one-tailed) providing further evidence to rule out a phonological output impairment as the source of the migration errors.

3.3.3 Orthographic processing

Finding that EC, NN, and EL made migration errors on silent reading tasks, succeeded in oral production tests without reading, and made errors on items where phoneme transposition cannot result in an apparent migration, is strong evidence against the phonological output stage as the source of the migration errors. An alternative source was orthography. We therefore conducted further tests to examine orthographic processing in the three participants.

One possibility to consider is that the participants have an impairment at the level of the orthographic input lexicon or in accessing that lexicon. In other words, the children may make migration errors because they have fewer lexical entries than is typical for their age, and thus guess at words and produce errors that are orthographically similar to the target when the target is unavailable. While a lexical impairment is unlikely given the children's normal irregular word reading, we wanted to investigate the possibility of lexical guessing specifically for migratable words.

From a long list of 244 migratable words (details in 3.4) that the children were asked to read aloud, we selected 176 target words for which at least one neighbour existed that was higher in frequency than the word's migration partner (e.g., for the target word *slept*, the neighbour *swept* is higher in frequency than the migration partner *spelt*). We selected these words because frequency may impact on the likelihood of whether or not a neighbour error occurs. We then determined if the children were more likely to make a reading error that was a neighbour or the migration partner (which was less frequent than at least one neighbour). The results were clear: Even for target words where neighbour words were higher in frequency than migration partners, all three children made significantly more migration errors than neighbour errors (EC: Fisher exact z = 3.42, p = .001 two-tailed, NN: Fisher exact z = 2.47, p = .013 two-tailed, EL: Fisher exact z = 2.43, p = .015 two-tailed).

3.3.4 Localising the origin of migration errors

These data taken together allow us to rule out lexical-orthographic and phonological output processing as the sources of letter position dyslexia, which suggests that the impairment is at the visual-orthographic analysis stage. As this stage is prelexical, migration errors should occur (1) in tasks that do not require lexical access (e.g. same-different judgements, Kinoshita & Norris, 2009), and (2) in reading tasks that require lexical processing or nonlexical processing (i.e., both word and nonword reading).

Same-different decision task. In this task, the participants were shown two words printed next to each other on a piece of paper with two spaces between them. The participants were requested to decide whether the two items were the same or not without reading them aloud. The children were not given any hints as to what might constitute a source of difference. The experimenter recorded the children's responses on a score sheet. There was no time limit. We presented a total of 120 word pairs. Half the word pairs were the same and half different, and half were migratable and half non-migratable, resulting in four categories of 30 item pairs each. The order of the items was randomised. In the 'same migratable' category we presented a migratable word twice (e.g., *three three*). In 'different order migratable' we presented a migratable word and its anagram partner (i.e., a second migratable word; e.g., *slate stale*). Similarly, in the category 'same non-migratable' a nonmigratable word was presented twice (e.g., *grain grain*), and 'different letter non-migratable' contained two words that differed with regards to their letter identity, and in which the two letters looked visually similar (e.g., *same some, stay slay*). The average number of letters of stimuli in each of the four categories was 5.1 (range 4-7).

EC judged significantly more pairs of different order migratable words (e.g., *diary–dairy*) as the same than the controls (see Table 5). EC's performance on this task was close to 50%, (i.e., chance). NN judged two same migratable words as different (e.g., *slime smile*) significantly more often than the controls. None of the other comparisons were significant (see Table 5).

NN and EL's level of accuracy on judging different migratable words was on par with the controls. However, NN took more than twice as long as the slowest control to complete this untimed task. When asked how he solved the task, NN reported that he looked at every letter in isolation and across the two words.

Nonword reading. We asked the participants to read aloud a list of 90 nonwords. The nonwords were presented as two columns on four pieces of paper. The list consisted of two categories of nonwords. There were 36 "migratable" nonwords in which a migration of the middle letters could create an existing word (e.g., *bron* as "born", *travel* as "travel")[6] and 54 "non-migratable" nonwords in which no migration could create another word. For the "non-migratable" nonwords there were two types: in 36 nonwords interior letters could migrate to form an orthographically legal nonword (e.g., *crog* as "corg", *gerft* as "greft"), and in 18 nonwords any middle letter migration would create an phonologically illegal letter string (e.g., *zirn, lerth*)[7]. The participants were not told whether they were reading words or nonwords. If the participants asked whether they were reading words or nonwords they were told that the tester was not allowed to tell them. We were interested in the occurrence of migration errors: word migrations (e.g., *tarvel* as 'travel') and nonword migrations (e.g., *tarvel* as 'tavrel'). The children also made other errors (e.g., *tarvel* as 'torrel' or as 'towel').

All three dyslexic participants made significantly more errors on nonwords that could migrate to words than the controls. EC, NN and EL did not make significantly more nonword-

[6] Since there were only six nonwords with the potential for their exterior letters to migrate to a word (*nare, pust, bist, stap, lats, neam*) we analysed all nonwords that could migrate to a word together.

[7] Note that it is almost impossible to create nonwords where the exterior letters cannot migrate to another orthographically legal position (e.g., *lerth* could migrate to *therl*).

to-nonword migrations (e.g., reading *frup* as 'furp') or other errors than the controls (e.g., reading *frup* as 'frop') (see Table 5 for details).

After reading the list of nonwords, EC went back to the beginning of the first page, pointed at the first item (a non-migratable word) and said: "I know what you did. This is a silly word." He then pointed to every single item and spontaneously performed a lexical decision task, during which he judged as a word almost every nonword that could migrate to a word (e.g., *bron, tarvel*).

Table 5. Error rates for controls and dyslexics on nonword reading and same different task.

	EC			**NN**			**EL**			**Controls**	
	N	*t*	*p*	*N*	*t*	*p*	*N*	*t*	*p*	Mean	SD
Nonword reading (n=90)											
Word migration errors	29	***6.69***	***<.01***	18	***3.86***	***<. 01***	24	***5.40***	***<.01***	3.0	3.6
Nonword migration errors	4	0.83	.22	6	1.76	.07	3	0.37	.36	2.2	2.0
Other errors	26	1.35	.12	14	-0.24	.41	9	-0.90	.21	15.8	7.0
Same different decisions (n=120)											
Diff order migratable (n=30)	16	***4.51***	***<.01***	5	0.08	.47	5	0.08	.47	4.8	2.3
Same migratable (n=30)	2	0.84	.22	***4***	***2.53***	***.03***	0	-0.84	.22	1.0	1.1
Diff letter non-migratable (n=30)	3	1.93	.06	0	-0.39	.36	0	-0.39	.36	0.5	1.2
Same non-migratable (n=30)	0	-0.81	.23	2	1.50	.10	0	-0.81	.23	0.7	0.8

Significant results (one-tailed) in bold italics.

The results of the tasks described above indicate that EC, NN and EL have an impairment at a stage that is earlier than the orthographic input lexicon, and that is shared by the lexical and sublexical routes. This stage is the orthographic-visual analyser. As outlined earlier, the analyser has three functions: letter position encoding, letter-to-word binding, and letter identification. We have seen in the experiments so far that the three participants have a deficit to the letter position encoding function. To evaluate the selectivity of the letter position encoding deficit, we explored the participants' abilities with respect to letter-to-word binding and to letter identification.

Letter-to-word binding. To assess if the children's difficulty in encoding letter positions occurred only within or also between words, we asked them to read a list of word pairs. Each pair was presented with one word next to the other, with a single space between them. The pairs appeared in a single centralised column on two laminated pages. The pairs were constructed so that "swapping" letters between words would create other existing words. We then examined whether the participants produced errors that were affected by the neighbouring word. Following Friedmann, Kerbel, and Shvimer's (2010) analysis, we attended to the following between-word errors: between-word horizontal migrations (i.e., letter swapping between word pairs presented in the same line, e.g., *clown frown* as 'flown crown' or 'clown crown'; *coat goal* as 'coal goat' or 'coat goat'), intrusions (e.g., *fight light* as 'flight light'), and omissions of the same letter that appears in the same position in the two words (e.g., *sport spell* as 'sort spell' or 'sport sell').

All three participants were within the normal range of between word errors. NN and EL were tested on a list of 35 word pairs (Friedmann, Castles, & Kohnen, 2011). They only made three and four letter-to-word binding errors respectively. A group of 48 readers with normal reading of words and nonwords in the same grade at school made an average of five letter-to-word binding errors on this list. Hence, NN and EL's letter-to-word binding abilities were in the normal range. EC was tested on an earlier version of this test that included 17 word pairs. He made two between-word migration errors. The 48 controls made, on average, 2.1 (SD = 1.89) between-word migration errors on this subset. Thus, the three participants who had a deficit in letter position encoding showed intact letter-to-word binding.

Letter identification abilities. NN and EL did not have any difficulties with letter identification as is evident from their flawless same-different decisions for all word pairs that differed in letter identity (see same-different decisions, Table 5 above). While EC made three errors on this task, this was not significantly different from the controls' performance. In addition, when we asked EC to name the letters in 40 migratable words, he named all letters correctly (but named letters in the incorrect order on two occasions). Hence, at least on the tasks presented to the participants, we found their letter identification skills to be unimpaired.

Thus, the children did not have difficulties in processing letter identity or letter-to-word binding, which suggests a selective deficit to the letter position component of the visual-orthographic analyser. So, our next step was to explore which item characteristics impacted on the likelihood of making a migration error.

3.4 Factors that modulate migration errors

In order to establish which factors impacted on the likelihood of a migration error we asked EC, NN and EL to read aloud a set of 244 migratable words (122 pairs). The 244 items comprised 184 new words that had not been previously read, and the 60 words from the migratable words list (see 3.2). The words were printed on paper and presented in two columns. The children were asked to read the words aloud with no time restrictions. This list enabled us to examine the following effects on migration errors: exteriority (does the migration occur for word-exterior letters or word-interior letters), adjacency (does the migration occur for adjacent or non-adjacent letters), frequency (does the migration occur from the lower frequent to the higher frequent word partner), and consonant-vowel status (does the migration involve consonants or vowels or both).

For each analysis, we selected words from this list to create a maximal difference for the variable of interest while matching for other potentially relevant factors (see Table 6). For example, we selected all of the words with a potential for adjacent migration and then selected non-adjacent words so that the two sets were matched as closely as possible on other variables that may impact on the likelihood of a migration errors (i.e., frequency, exteriority) and other important word characteristics (e.g., number of letters, regularity, length). We used the N-Watch program to retrieve information about frequency and regularity (Davis, 2005).

We used Fisher's exact tests to assess whether more migrations were made on one set (e.g., words that allow for adjacent migrations) vs. the other (e.g., words that allow only for non-adjacent migrations). This was assessed separately for each of the three dyslexic participants.

Exteriority. To compare migrations of middle letters and of exterior letters, the list contained word pairs with a potential for migration of the middle letters (e.g., *weird–wired; snug* - *sung*) and words with a potential for a migration involving the first or last letters (e.g., *lots–lost; coast* - *coats*). A migration was characterised as interior if the exterior letters were the same in both word pair members. All other types of migrations were called exterior. We matched 24 words with exterior migration to a set of 24 words with interior migration on the following variables: length, adjacency of migration, frequency and regularity.

All three participants made significantly more errors on interior than exterior migration words (see Table 6 for details).

Table 6. *EC, NN and EL's migration errors: Effects of exteriority, adjacency, and frequency.*

Effects	*N*	Word characteristics (means)						EC			NN			EL		
		Ext	Adj	Log_10 _fq	Log_10 fq_diff	Regula-rity	Length (Letters)	Mig errors	z	*p*	Mig errors	z	*p*	Mig errors	z	*p*
Exteriority																
Exterior	24	1	.5	1.2	.9	.6	4.3	3			5			2		
Interior	24	0	.6	1.1	.9	.6	4.4	9	--	***.047***	13	--	***.018***	9	--	***.018***
Adjacency																
Adjacent	72	.3	1	1.1	.7	.5	4.8	17			33			20		
Non-adj	72	.3	0	1.1	.7	.5	4.9	8	1.75	***.040***	8	4.42	***<.001***	11	1.62	.053
Adjacent-interior																
Adjacent	38	0	1	1.1	.7	.4	5.4	7			13			8		
Non-adj	38	0	0	1.1	.6	.5	5.4	10	--	.291	7	--	.096	6	--	.384
Frequency (whole set: median split)																
High	122	.3	.3	1.0	.7	.4	5.3	13			33			15		
Low	122	.3	.3	1.1	.7	.5	5.3	29	2.54	***.006***	28	0.59	.28	32	2.59	***.005***
Frequency (difference between high and low fq member of 1 or more and lower fq member with a log fq of <1)																
High	27	.3	.3	1.8	1.5	.4	5.1	1			6			1		
Low	27	.3	.3	.3	1.5	.5	5.1	6	--	***.050***	9	--	.272	10	--	***.003***
Frequency (in interior migration words)																
High	91	0	.3	1.3	.6	.4	5.7	14			22			17		
Low	91	0	.3	.6	.6	.4	5.7	24	1.64	***.050***	27	0.66	.253	25	1.23	.110
Consonant (C) / Vowel (V) status of migrating letters																
CC	40	.3	.5	1.1	.6	.6	5.3	5			14			6		
CV/VC	40	.3	.6	1.3	.7	.5	5.2	10	--	.126	17	--	.323	13	--	.057

Notes. Exteriority, adjacency and regularity are binary characteristics. Frequency and regularity are based on N-Watch (Davis, 2005). We are reporting means for two item sets on the following variables: exteriority, adjacency, frequency, regularity and length. Significant *p*-values (one-tailed) are in bold italics.

Letter adjacency. To evaluate the effect of letter adjacency, the list contained words with a potential for adjacent migration (e.g., *wrap–warp; snug–sung*) and non-adjacent migration (e.g., *smile–slime*, *except–expect*). We classified a migration as adjacent if the letters that swapped positions were immediately next to each other. The lists included 72 words with a lexical potential for adjacent migration (e.g., *wrap–warp*) and 172 words with a lexical potential for non-adjacent migration (e.g., *stale–slate*). Again, we compared the 72 adjacent migration words to a subset of 72 non-adjacent migration words that we selected to match relevant item characteristics of the adjacent migration ones (see Table 6).

EC and NN made significantly more migration errors on adjacent than non-adjacent words, with EL showing a trend in the same direction (see Table 6 for details). However, when we examined the number of migrations on words with word-interior migration only, the children did not make significantly more migrations on adjacent than non-adjacent letters (see Table 6 for details).

Frequency. The list contained words that differed widely in log frequency of occurrence (range: 0 – 3.36) as calculated by N-Watch (Davis, 2005). We performed three comparisons. First, we did a simple median split, investigating whether the children were more likely to make a migration error on the lower frequency word of a pair. We divided the set of 244 migratable words into two sets: the lower frequency member vs. the higher frequency member of a pair. Since the two members of a pair are always of the same length, and also do not differ regarding the place where the migration occurs (interior-exterior; adjacent-non-adjacent), the two sets naturally did not differ on any of these other potentially important factors (see Table 6 for details).

However, this simple median split did not create a significant difference in frequency between the two sets (higher frequency pair members = 1.1; lower pair members = 1.0). In order to increase the difference in frequency we performed an additional analysis. Here, we only included migration pairs where the difference in log frequency between the two words was 1 or higher. We then selected the pairs where the lower frequency word had a log frequency lower than 1. For the resulting 54 words (27 pairs) we compared the number of migration errors on the higher frequency vs. the lower frequency member.

In a third investigation we only looked at high versus low frequency items in words with interior migration.

On the median split comparison, EC and EL were significantly more likely to make a migration error on the lower frequency words. NN made almost the same number of migration errors across the two sets. For the comparison with the high difference in frequency, both EC and EL made significantly more errors on the lower frequency member of a pair. However, NN did not show a tendency to make more migration errors on lower frequency words. When analysing frequency differences only for words with interior migration potential, we found that only EC made significantly more errors on the lower frequency words.

Consonant-vowel status. Migrations can affect consonants only (e.g., smile–smile), vowels only (e.g., trial–trail) or both consonants and vowels (e.g., sang–snag). Previous research with adults has found migration effects for consonants only (e.g., Perea & Lupker, 2004), while Hebrew-reading letter position dyslexics did not show a clear tendency regarding consonant-vowel status (Friedmann & Rahamim, 2007). Our list did not contain enough vowel-only migrations, but we could determine whether the children in this study were more likely to transpose consonants with consonants (*slept–spelt*) or whether they would also transpose consonants with vowels (or vice versa) (*wrap–warp*). We were able to match 40 words with consonant-consonant migration to 40 words with consonant–vowel migrations (see Table 6).

There was no difference in the number of migration errors between consonant–consonant and consonant–vowel migrations for EC, NN, or EL. This result is important because it rules out a specific deficit in vowel letters as the source of the migration errors the participants made. Individuals with vowel letter dyslexia only make migrations that involve the position of vowel letters relative to other letters in the word (namely, they make consonant–vowel migrations but not consonant–consonant errors, Khentov-Kraus & Friedmann, 2011). The findings according to which consonant–vowel and consonant–consonant migrations occurred to the same degree indicate that they did not result from vowel letter dyslexia.

4. Discussion

We will now return to the three questions we sought to answer in this paper:

Does selective letter position dyslexia exist in English?

This paper is the first to report cases of selective letter position dyslexia in English. Importantly, these children's difficulties in coding letter positions would have been missed, had we not given them a specific type of words to read: migratable words. It appears that letter position coding difficulties are very easy to overlook when assessing English readers (and probably other languages) because the most commonly used assessments do not include a subset of migratable words.

The fact that our three letter position dyslexics were identified 10 years after the publication of the first (acquired) cases in Hebrew raises the question of whether letter position dyslexia is a rare subtype of dyslexia in English. While questions relating to incidence are best answered in studies using whole birth cohorts, we would like to make three points: First, we only started using the migratable words list in the year in which we identified these letter position dyslexics. We may have missed other children with this difficulty previously. Second, we did not actively screen for children with this type of difficulty. These three children's parents were concerned about their children's spelling and (in NN's case) reading and came to see us. It was only when the children made migration errors during testing that we became aware of their letter position coding difficulties. Third, experienced clinicians and special education teachers are not surprised about the finding that children have difficulties in coding of letter positions–they see children make migration errors in their clinics and schools. Therefore, it would not be surprising to us if difficulties in letter position coding were found to be not very rare at all, even in English.

Two participants in this study were referred to us because their parents and/or teachers were concerned about the children's progress in reading (but there were no concerns about EL's reading). Yet, recent previous reading assessments had not shown any areas of concern in the form of below average performance. Sometimes test results in the average range indicate that the worries of educators and parents about a child's reading progress are unsubstantiated. Other times it may be the case that assessment tools are not sensitive enough to tell us about the reason and origin of a difficulty. Thus, the answer to the first question we set out to address, "Does selective letter position dyslexia exist in English?" is Yes.

Which component(s) of the reading system are responsible for the production of migration errors?

We assessed these three participants in detail on tests used with previous cases of selective letter position dyslexia in Hebrew and Arabic and found that the pattern of performance of the English reading children were very similar to those of previously described letter position dyslexics. As the summary in Table 7 shows, between the three participants we found every single feature of letter position dyslexia as described in the previous literature.

Table 7. Summary of results

Performance Pattern	**EC**	**NN**	**EL**
High number of migration errors in reading aloud	✓	✓	✓
Normal reading of non-migratable words	✓	✓	✓
Normal reading of non-migratable nonwords	✓	✓	✓
Misjudging migratable nonwords as words	✓	✓	✓
Defining migratable words as their migration partner	✓	✓	✓
Judging two different migratable words as same	✓	✗	✗
Reading migratable nonwords as words	✓	✓	✓
More migration errors on words with interior than exterior migrations	✓	✓	✓
More migration errors on words with adjacent than non-adjacent migrations	✓	✓	✗
More migration errors on low frequency than high frequency words	✓	✗	✓
Normal level of between words migratations	✓	✓	✓
Normal letter identification skills	✓	✓	✓
Normal phonological awareness skills	✓	✓	✓
No migration errors on spoken repetition tasks	✓	not tested	not tested

We used these same tasks to find out which component(s) of the reading system are responsible for the production of migration errors. As summarised in the Introduction, migration errors in reading aloud could be produced due to deficits in three locations in the processing model (Figure 1): (1) the phonemic output buffer, (2) difficulties with accessing the orthographic lexicon or lexical guessing: accessing words that are orthographically similar to the target word from the orthographic lexicon, or (3) the letter position coding function of the orthographic–visual analyser.

It is not a deficit to the phonemic output buffer. EC, NN, and EL's pattern of performance showed that the level of the phonemic output buffer was improbable as a source of their migration errors. First, all three participants performed in the normal range on tasks that rely on the phonemic output buffer: phonemic awareness tasks including phoneme segmentation, phoneme deletion, and the most phonemic output buffer-demanding task – spoonerisms. They also showed normal nonword repetition, and EC, who was asked to repeat all the words and nonwords he read, made no migration errors in repetition. These findings indicate that the participants' phonemic output buffer is not impaired. Second, they continued to make migration errors in silent reading tasks, which do not require the use of the phonemic output buffer: visual lexical decision, same–different judgements, and definitions.

Further, only a third of the words administered to EC, NN and EL were such that a migration error could have been also accounted for by a phoneme migration (e.g., *fist–fits*). The majority of words we presented required a reordering of the letters to produce a migration error (e.g., *could–cloud*), rather than a reordering of phonemes. An analysis of their migration errors indicated that none of the participants showed a tendency to produce more migration errors for words that could be transposed at the phoneme level.

In summary, the data speaks strongly against the phonological output stage as the source of migration errors for EC, NN, and EL. It is possible that phonology is activated in the silent reading tasks. However, the participants' good performance on word and nonword production and repetition, and the lack of any migration errors in phonological output tasks other than reading aloud of migratable words, provide solid evidence against a phonological output impairment.

It is not a deficit to the orthographic input lexicon. Lexical guessing also appears an unlikely source for the children's migration errors. This interpretation would see migration responses occurring as a result of lexical access to words that are orthographically similar to a target word. However, EC, NN, and EL made significantly more migration errors than other neighbour errors, and hence lexical guessing does not appear to be a satisfactory explanation for migration errors. These results do not support the idea that lexical guessing is responsible for the migration errors. Lexical guessing may occur due to a deficit in the orthographic input lexicon, for example, a deficit in accessing orthographic representations or storing a sufficient number of representations. This type of lexical deficit is unlikely to explain the pattern for EC, NN and EL given that all three participants were normal at reading irregular words aloud.

More evidence against placing the deficit in the orthographic input lexicon is the participants' pattern of nonwords reading. Had the deficit been purely a deficit of misselection in the orthographic input lexicon (i.e., mistakenly selecting the migration partner of the target word), there would be no explanation for the fact that the participants made migration errors in reading nonwords. Lastly, it would require a new model of the lexicon that would allow for a selective impairment that causes activation of migration partners but not of words that are visually similar to the target in other ways.

It is a deficit to the letter position encoding function in the orthographic-visual analyser. Orthographic-visual analysis occurs prior to lexical and nonlexical processing (see Figure 1). Hence, an impairment at this stage should affect both lexical and nonlexical reading. Indeed, all three participants not only made migration errors when reading words, they also made migration errors when reading nonwords. Therefore the data of our study is most consistent with the interpretation that migrations in these three participants with letter position dyslexia originate from a deficit in coding letter positions at the level of orthographic-visual analysis.

However, if migrations are single-handedly produced by a difficulty in coding letter positions, why did EC, NN or EL not make more migrations in nonword reading that led to another nonword response (e.g., *gerp* as “grep”)? At this point in time, we can only speculate why this is so. One possibility is that the hypothesised serial processing mode of the nonlexical route (e.g., Friedmann & Gvion, 2001; Rastle & Coltheart, 1998) promotes a more refined coding of positions and hence attracts fewer migration errors. This is in line with Friedmann and Rahamim’s (in press) finding that children’s migration error rate decreases significantly when they adopt a grapheme-by-grapheme based reading strategy.

One may wonder how specific and how dysfunctional this impairment is. For the participants in this study, while performing in the lowest 3% for their grade on reading a list of migratable words, they all scored within the normal range on every other test tapping the subskills necessary to read single words and nonwords (see Figure 1). These results indicate a very specific impairment of the letter position coding system which only affects reading accuracy of words that have migration partners (anagrams; transposition neighbours) and nonwords that can migrate to words. The only other common difficulty was that all three children were poor spellers. It seems plausible that a difficulty in coding letter positions would hamper spelling progress. However, the children’s spelling was not characterised by a difficulty concerning letter order which is consummate with the findings for Hebrew where letter position dyslexia and letter position dysgraphia do not necessarily co-occur (Gvion & Friedmann, 2010).

It is important to emphasise that children with letter position dyslexia are not unique in making migration errors. In fact, English-speaking beginner readers make the same type of mistake when attempting to read aloud migratable words and nonwords (e.g., Kohnen & Castles, in press; Perea & Estevez, 2008). Thus, it is not the error itself that is of concern in letter position dyslexia, rather it is the number of these errors. In this context it is also important to mention that the prevalence of migration errors in the general population of children with dyslexia is currently unknown. Friedmann and Rahamim (2007) report that children with neglect dyslexia or surface dyslexia make almost no migration errors, but further investigation across a range of dyslexia subtypes is needed.

What characteristics of words impact on the likelihood of a migration error occurring?

Across the three participants, we replicated every effect on migrations in letter position dyslexia that was found in previous research (Friedmann & Gvion, 2001; Friedmann & Rahamim, 2007). Migrations were more likely to occur for low frequency than for high frequency words, in adjacent than non–adjacent letters, and for word–interior than exterior migrations. The consonant or vowel status of the migrating letters did not impact on the likelihood of a migration occurring. There was some variability between the three children such that we did not find every effect for all children. This was also true for Friedmann and Rahamim's group of 11 participants. This is not surprising as we would expect a certain degree of variability within every group of participants, even those selected for a particular feature in their language processing system (in this case making many migration errors). The variability could occur due to differences in other processing components or general ability. It is also possible that exterior factors (e.g., attention, tiredness) or even the use of strategies (e.g., NN's approach to the same–different task) led to some variability.

Similar to previous cases of letter position dyslexia, the three participants in this study showed higher levels of migrations for adjacent transpositions. All current models of written word recognition that can explain letter-transposition effects would predict this (e.g., Davis & Bowers, 2006; Gomez, Ratcliff, & Perea, 2008; Grainger & van Heuven, 2003; Whitney, 2001). The data from letter position dyslexics shows a non-negligible number of migrations for non-adjacent (and multiple) migrations, including our favourite error made by all three participants–reading *pirates* as 'parties'. Ultimately, input coding schemes in computational models need to be able to simulate not only that the majority of migration errors occur for adjacent transpositions, but also allow for a small number of non-adjacent and multiple migrations in impaired systems.

The finding that exterior letters are less likely to be affected by migration than interior letters is in line with the findings for letter position dyslexia in other languages (Friedmann & Gvion, 2001; Friedmann & Haddad-Hanna, 2012; Friedmann & Rahamim, 2007) and indeed normal readers (Pitchford, Ledgeway, & Masterson, 2008; Schoonbaert & Grainger, 2004). It seems that exterior letters are more resilient to migration than interior letters. It may be that position coding for exterior letters is less ambiguous, possibly because exterior letters have a perceptual advantage, being adjacent to a space and with fewer neighbouring letters introducing noise to the position coding. Exterior letters may also act as processing anchors and may be given more processing resources. For example, exterior letters may be processed first and more thoroughly before interior letters (see Friedmann & Rahamim, 2007). Exterior letters have also been found to have a special processing status in research with developing readers that was not restricted to migratable words (e.g., Jordan, Thomas, Patching, & Scott-Brown, 2003). There is evidence to suggest that exterior letters (especially initial letters) have a special status in a lexical representation as, for example, shown by the high degree of overlap between target spelling and spelling errors (e.g., Goldrick, Folk, & Rapp, 2010). Thus, it may be the case that the resilience of exterior letters is not a purely prelexical letter position coding phenomenon: There may be factors associated with the nature of lexical representations that contribute to this effect.

While a degree of variability in performance is expected, the lack of a frequency effect for NN in reading migratable words requires some consideration because Friedmann and Rahamim (2007) found strong and significant frequency effects for all participants. It was also the frequency effect that led Friedmann and Rahamim to argue that letter position coding was imprecise rather than inaccurate. Therefore, we decided to investigate NN's lack of frequency effect in more detail. In particular, we assessed whether NN showed a frequency effect for other, non-migratable words. On his initial referral to our research group, NN had read a set of 58 irregular words (mean length 5.6 letters, range: 3–10), and we used these to investigate this question. NN made 19 errors on these words. On average, the correctly read words were 5.4 letters long and had a log frequency of 1.9, while the incorrectly read words were 5.9 letters long and had a log frequency of 1.1. The misread words were significantly less frequent but not significantly longer than the words read correctly (frequency: two sample t test $t(56)=4.26$ $p < .001$; length: two sample t test $t(56)=1.37$ $p = .18$ two-tailed). Thus NN can be said to show the standard, well-established frequency effect in reading, and this cannot account for the lack of a frequency effect on migratable word reading.

The lack of frequency effect in NN's reading may suggest a different locus of impairment from EC and EL. One possibility is a general difficulty in order processing extending beyond just letters. Future investigations of letter position dyslexia in English should examine the extent to which order processing deficits concern items other than letters. The most obvious domain is that of numbers. However, we note that recent experiments with Hebrew letter position dyslexics by Friedmann, et al. (2010) show that order processing for orthography is independent of order processing for digits. That is, participants can show dissociations between position encoding for letters and digits.

We think that the most parsimonious account is an orthography specific deficit in letter position encoding for all participants. First, all three children made migration errors on nonwords that led to other nonwords (e.g., reading *glip* as 'gilp'). This cannot happen at the lexical stage. Second, Kinoshita and Norris (2009) argue convincingly that same–different decisions are the appropriate task to tap prelexical processing. Therefore, poor decisions on the sameness of migratable items also point to a prelexical difficulty.

In sum then, we have presented the first three pure cases of letter position dyslexia in English. The developmental cases in our study resemble previous cases of acquired and developmental letter position dyslexia described in Hebrew and Arabic. Our data is most readily explained by a deficit in the prelexical letter order processing stage, whereas deficits in the phonological output stage or in the orthographic lexicon cannot account for the reading pattern of our participants with letter position dyslexia. We have demonstrated that in order to identify letter position coding deficits it is essential to use appropriate stimuli (i.e., migratable words and nonwords), as without these stimuli such deficits can be easily missed.

References

Broom, Y. M., & Doctor, E. A. (1995). Developmental surface dyslexia: a case study of the efficacy of a remediation programme. *Cognitive Neuropsychology, 12*, 69–110.

Brunsdon, R., Coltheart, M., & Nickels, L. (2006). Severe developmental letter processing impairment: a treatment case study. *Cognitive Neuropsychology, 23*, 795–821.

Castles, A., & Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition, 47*, 149–180.

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*, 67-88.

Castles, A., Crichton, A., & Prior, M. (2010). Developmental dissociations between reading and comprehension: evidence from two cases of hyperlexia. *Cortex, 46*, 1238–1247.

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,* 1196–1208.

Davis, C. (2005). N-Watch: a program for deriving neighborhood size and other psycholinguistic statistics. *Behavior Research Methods, 37*, 65–70.

Davis, C., & Bowers, J. S. (2006). Contrasting five different theories of letter position coding: Evidence from orthographic similarity effects. *Journal of Experimental Psychology, 32*, 535–557.

Dodd, B., Holm, A., Oerlemans, M., & McCormick, M. (1996). *Queensland University inventory of literacy (QUIL)*. St Lucia: The University of Queensland Press.

Frederickson, N., Frith, U., & Reason, R. (1997). *Phonological assessment battery (PhAB)*. Windsor: NFER-Nelson.

Friedmann, N., Castles, A., & Kohnen, S. (2011). *FriCasKo - A screening test for dyslexia subtypes*. Unpulished Test.

Friedmann, N., Dotan, D., & Rahamim, E. (2010). Is the visual analyzer orthographic-specific? Reading words and numbers in letter position dyslexia. *Cortex, 46,* 982–1004.

Friedmann, N., & Gvion, A. (2001). Letter position dyslexia. *Cognitive Neuropsychology, 18*, 673–696.

Friedmann, N., & Gvion, A. (2005). Letter form as a constraint for errors in neglect dyslexia and letter position dyslexia. *Behavioural Neurology, 16*, 145–158.

Friedmann, N., & Haddad-Hanna, M. (2012). Letter position dyslexia in Arabic: From form to position. *Behavioural Neurology, 25*(3), 193-203.

Friedmann, N., & Haddad-Hanna, M. (in press). Types of developmental dyslexia in Arabic. In Saiegh-Haddad, E., & Joshi, M. editors. *Arabic literacy: theoretical insights and practical challenges. Language and literacy series.* Springer: The Netherlands.

Friedmann, N., Kerbel, N., & Shvimer, L. (2010). Developmental attentional dyslexia. *Cortex, 46*, 1216–1237.

Friedmann, N., & Lukov, L. (2008). Developmental surface dyslexias. *Cortex, 44*, 1146–1160.
Friedmann, N., & Rahamim, E. (2007). Developmental letter position dyslexia. *Journal of Neuropsychology, 1*, 201–236.
Friedmann, N., & Rahamim, E. (in press). What can reduce migrations in letter position dyslexia? *Journal of Research in Reading*.
Goldrick, M., Folk, J.R., & Rapp, B. (2010). Mrs. Malaprop's neighborhood: Using word errors to reveal neighborhood structure. *Journal of Memory and Language, 62,* 113-134.
Gomez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: a model of letter position coding. *Psychological Review, 115,* 577–600.
Grainger, J., & van Heuven, W. J. B. (2003). Modelling letter position coding in printed word perception. In P. Bonin (Ed.), *The mental lexicon* (pp. 1–23). New York: Nova Science.
Gvion, A., & Friedmann, N. (2010). Letter position dysgraphia. *Cortex, 46,* 1100-1113.
Jordan, T. R., Thomas, S. M., Patching, G. R., & Scott-Brown, K. C. (2003). Assessing the importance of letter pairs in initial, exterior, and interior positions in reading. *Journal of Experimental Psychology: Learning, Memory and Cognition, 29*, 883-893.
Khentov-Kraus, L., & Friedmann, N. (2011). Dyslexia in vowel letters (DIVL). *Language and Brain*, *10*, 65-106.
Kinoshita, S., & Norris, D. (2009). Transposed-letter priming of pre-lexical orthographic representations. *Journal of Experimental Psychology: Learning, Memory and Cognition, 35,* 1-18.
Kohnen, S., & Castles, A. (in press). *Pirates at parties: letter position processing in developing readers*. Journal of Experimental Child Psychology.
Korkman, M., Kirk, U., & Kemp, S. (1998). *A developmental neuropsychological assessment (NEPSY)*. Texas, USA: The Psychological Corporation.
Martin, F., & Pratt, C. (2001). *Nonword Reading Test*. Melbourne, Australia: ACER.
Masterson, J., Stuart, M., Dixon, M., & Lovejoy, S. (2010). Children's printed word database: continuities and changes over time in children's early reading vocabulary. *British Journal of Psychology, 101*, 221-242.
Neale, M. D. (1999). *Neale analysis of reading ability* (3rd ed.). Camberwell: ACER.
Perea, M., Duñabeitia , J. A., & Carreiras, M. (2008). Transposed-letter priming effects for close versus distant transpositions. *Experimental Psychology, 55*, 384-393.
Perea, M., & Estevez, A. (2008). Transposed-letter similarity effects in naming pseudowords: evidence from children and adults. *European Journal of Cognitive Psychology, 20,* 33-46.
Perea, M. & Lupker, S.J. (2004). Can CANISO activate CASINO? Transposed-letter similarity effects with nonadjacent letter positions. *Journal of Memory and Language, 51,* 231-246.
Pitchford, N. J., Ledgeway, T., & Masterson, J. (2008). Effect of orthographic processes on letter position encoding. *Journal of Research in Reading, 31*(1), 97-116.
Rastle, K., & Coltheart, M. (1998). Whammies and double whammies: the effect of length on nonword reading. *Psychonomic Bulletin and Review, 5*, 277-282.
Rayner, K., Murphy, L.A., Henderson, J.M., & Pollatsek, A. (1989). Selective attentional dyslexia. *Cognitive Neuropsychology, 6,* 357-378.
Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: effects of repeated and transposed letters. *Language and Cognitive Processes, 19,* 333–367.
Snowling, M., & Hulme, C. (1989). A longitudinal case study of developmental phonological dyslexia. *Cognitive Neuropsychology, 6*, 379–401.
Temple C. M. (1997). *Developmental cognitive neuropsychology*. Hove, East Sussex, UK: Psychology Press.
Temple, C. M., & Marshall, J. C. (1983). A case study of developmental phonological dyslexia. *The British Journal of Psychology, 74*, 517–533.
The Psychological Corporation. (2002). *Wechsler Individual Achievement Test (WIAT)* (2nd ed.). San Antonio, TX: The Psychological Corporation.
Torgesen, J., Wagner, R., & Rashotte, C. (1999). *Test of word reading efficiency* (TOWRE). Pro-Ed, Texas.
Wagner, R.K., Torgesen, J.K., & Rashotte, C.A. (1999). Comprehensive test of phonological processing (CTOPP). Austin, TX: Pro-Ed.
Whitney, C. (2001). How the brain encodes the order of letters in a printed word: the SERIOL model and selective literature review. *Psychonomic Bulletin and Review, 8*, 221–243.