

**Letter Position Processing in
Developing and Skilled Readers**

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General Summary

This thesis aims to systematically investigate the cognitive mechanisms thought to be involved in letter position processing and its development.

Chapter 1 describes the theoretical framework upon which this thesis is based, as well as the motivation for the studies reported in Chapters 2 through 5.

Chapter 2 reports on a study that uses the masked transposed-letter (TL) priming task to track the development of letter position coding in children learning to read (ages 7-12 years) as well as skilled adult readers. This study extends on previous research by disentangling changes in letter position coding from changes in letter identity. The results suggest that letter position coding becomes increasingly refined as reading develops.

Chapter 3 investigates whether changes across development in sensitivity to letter position manipulations – such as those reported in Chapter 2 – are driven by lexical development. This hypothesis is tested by investigating whether lexical skills influence masked TL priming effects in University students. The results show no significant relationship between lexical skill and TL priming.

The study presented in **Chapter 4** adopts a novel variant of the Reicher-Wheeler task to further explore whether lexical development drives changes in sensitivity to letter position manipulations. In this task, participants are asked to report the identity of a letter at a specified position within three lexical contexts: anagram words (e.g. *form* – which has the anagram partner, *from*), pseudowords (e.g., *pilf* – *plif*) and illegal nonwords (e.g. *ftkl* – *ftl*). The results suggest that lexical influences on letter position processing increase with development.

Chapter 5 investigates the locus of impairment in three children with developmental letter position dyslexia, who were identified based on their excessive letter position errors (e.g., reading *slime* as “smile”). Participants’ performance on various tasks, including reading aloud, lexical decision and same-different decision, is evaluated. The

findings suggest that letter position dyslexia is most likely caused by a deficit to the letter position coding mechanism within the orthographic-visual analyser.

Chapter 6 brings together the most important findings from the work reported in this thesis, and considers their implications for past and future studies investigating the development of letter position processing.

Statement of Candidate

I, Yvette Kezilas, certify that the content in this thesis has not previously been submitted for a higher degree to any other university or institution. This thesis is an original piece of research written by myself, and any assistance I have received in the preparation of this thesis has been appropriately acknowledged. All information sources that have contributed to the thesis have also been acknowledged throughout the thesis.

The research reported in thesis has received ethical approval by the Human Research Ethics Committee (project reference no: 5201200947).



.....
Yvette Kezilas (Student ID: 42739055)

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Chapter 1

General Introduction

General Introduction

Reading a passage of text requires the mind to be somewhat sensitive to the position of letters within words. Without sensitivity to letter position, words would frequently be misread (e.g., *pat* might be misread as “apt” or “tap”, *slime* as “smile” or “miles”), making the experience of reading unenjoyable at best, and incomprehensible at worst. While letter position processing is typically sensitive enough to enable the fine discrimination between words, it is also surprisingly flexible, enabling these words to be read with apparently little cognitive effort. This intriguing balance between precision and flexibility has led to decades of research investigating letter position effects in skilled adult readers (e.g., Andrews, 1996; Andrews & Lo, 2012; Forster, Davis, Shoknecht, & Carter, 1987; Grainger & Whitney, 2004; Lee & Taft, 2009, 2011; Lupker & Davis, 2009; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2003; Perea & Lupker, 2004; Rayner, White, Johnson, & Liversedge, 2006), as well as various attempts to simulate these findings using various computational models of visual word recognition (e.g., Davis, 2010; Gomez, Ratcliff, & Perea, 2008; Whitney, 2001; see Grainger & van Heuven, 2003 for a review).

How letter position processing progresses over the course of reading development has received considerably less research attention. Is the apparent fine balance between precision and flexibility that characterises letter position processing in skilled adult readers a stable feature of the reading system, or does it change across development? And if letter position processing does change, what is the nature of this change? Is it that relatively flexible letter position processing in skilled adult readers reflects a refinement of coarser processing earlier on in development? Or is flexible letter position processing a hallmark of skilled reading, with older readers processing letter position more coarsely than younger readers? And what causes letter position processing to develop atypically in children with letter position dyslexia?

The few studies that have addressed these research questions have provided

inconclusive findings. I argue that the confusion within the developmental literature is compounded by a tendency amongst studies to focus predominately on the mechanisms underlying letter position encoding, without careful consideration of the various other cognitive mechanisms that are likely to change simultaneously as reading develops. The aim of this thesis is to therefore take a broader approach to letter position development in an attempt to resolve some of the ambiguities within the literature.

In this introductory chapter, I will first describe the framework upon which the research in this thesis is based. I will then detail the specific cognitive mechanisms that will be subject to investigation in subsequent chapters, and describe how each of these mechanisms – as well as their complex interactions with one another – is paramount to informing our understanding of both typical and atypical letter position development.

A Dual-Route Approach to Reading

The research reported in this thesis is based broadly within the architecture of the dual-route cascaded model of visual word recognition and reading aloud (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). In its current instantiation, the dual-route model is designed to simulate skilled adult reading. However, the general framework upon which the model is based has been used for decades to inform verbal predictions of both typical and atypical reading development (e.g., Grainger & Ziegler, 2011; Marshall, 1984; Castles, Bates, & Coltheart, 2006), deeming it an appropriate model for contextualising the work reported in this thesis. Further verification of the model's ability to account for developmental findings comes from recent successful attempts to simulate how children learn to read (Pritchard, Coltheart, Marinus, & Castles, submitted).

The dual-route model is depicted in Figure 1. Following the model, when a word is encountered in print, its visual features are first recognised, and then submitted for orthographic-visual analysis. The orthographic-visual analyser is responsible for identifying each letter in each position within the word. For example, for the written word

ship, the representation for the letter *S* is activated in the first position or ‘slot’, the letter *H* in the second, the letter *I* in the third, and the letter *P* in the fourth.

Following orthographic-visual analysis, the word 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 phonological output lexicon via the semantic system), and (3) the nonlexical route (grapheme to phoneme conversion). In typical readers, the lexical and lexical-semantic routes process all words within a reader’s orthographic input lexicon – which stores orthographic representations (or memory traces) for familiar words – but fails to successfully process nonwords (e.g., *borp*, *thurnlurse*) or words that are unknown to the reader. In contrast, the nonlexical route successfully sounds out nonwords and words that follow typical letter to sound rules (‘regular words’ such as *surf*, *blame* and *hand*), but fails to provide accurate pronunciation for irregular words (such as *yacht*, *come*, and *friend*).

If spoken output is required, as is the case for reading aloud, the phonemes within the word are then assembled and held active in the phonological output buffer until a response is made. Similar to the way in which letter identities are processed by the orthographic-visual analyser, the phonemes in the word to be pronounced are assigned to their appropriate position within the word. For example, for the written word *ship*, the phoneme /sh/ is activated in the first phoneme position or ‘slot’, the /i/ in the second phoneme position, and the /p/ in the third phoneme position.

Three components within the dual-route model are particularly relevant to the work presented in this thesis: (1) the orthographic-visual analyser, (2) the orthographic input lexicon, and (3) the phonological output buffer. The role that each of these mechanisms play in letter position processing, and their relevance to the research reported in this thesis, will be detailed in the following sections.

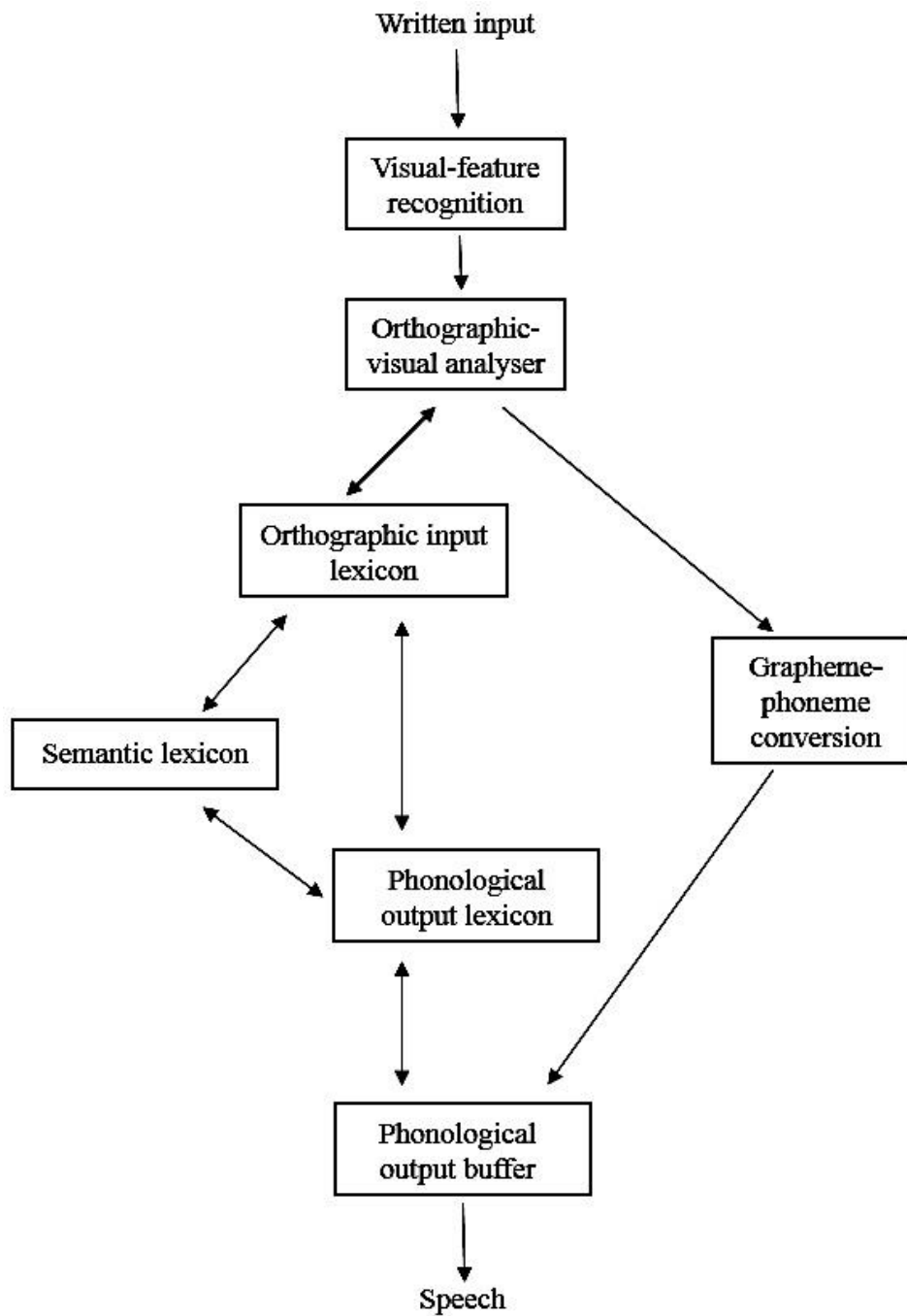


Figure 1. Dual-route cascaded model of visual word recognition and reading aloud (Coltheart et al., 2001). Single-headed arrows indicated feed-forward activation (reflecting the cascaded nature of the model). Double-headed arrows indicate feed-forward and feed-back activation (reflecting the interactive nature of the model).

The Orthographic-Visual Analyser

Like many models that provide a broad framework of visual word recognition and reading aloud (e.g., Interactive Activation model, McClelland & Rumelhart, 1981; Connectionist Dual Process model, Zorzi, Houghton, & Butterworth, 1998; but see Seidenberg & McClelland, 1989), the dual-route model assumes that letter identities are rigidly assigned to their correct position within a word. However, a multitude of studies showing that readers are more likely to misperceive *jugde* as a word (where two letters within the word JUDGE have been transposed) than they are to misperceive *jupte* as a word (where two letters have been substituted with different letter identities), suggests that the mechanisms underlying letter position and letter identity coding are separable (e.g., Lupker, Perea, & Davis, 2008; Perea & Lupker, 2003; Perea & Lupker, 2004). Further evidence for distinct functions underpinning letter position and identity coding comes from studies showing that children and adults with letter position dyslexia have great difficulty processing letter position (resulting in frequent ‘letter position errors’, such as reading *slime* as “smile”) while letter identity processing remains intact (Friedmann & Rahamim, 2007; Friedmann, Dotan, & Rahamim, 2010; Friedmann & Haddad-Hanna, 2012; Kohnen, Nickels, Castles, Friedmann, & McArthur, 2012; Kezilas, Kohnen, McKague, & Castles, 2014; see Chapter 5 of this thesis).

In response to these findings, various input coding schemes have been proposed to replace the ‘front-end’ of reading models that currently regard letter identity and position as integral dimensions (e.g., Spatial Coding model, Davis, 2010; Open-bigram model, Grainger & van Heuven, 2003; Overlap model, Gomez et al., 2008; Bayesian reader, Norris, 2006; Norris, Kinoshita, & Casteren 2010; SERIOL model, Whitney, 2001). These input coding schemes vary considerably in how they regard letter position to be coded. For example, some schemes suggest that the misperception of the pseudoword *jugde* as its base word JUDGE reflects generic perceptual noise in the visual system (e.g., Overlap model,

Gomez et al., 2008; Bayesian reader, Norris et al., 2010), whereas others suggest that these effects arise due to positional uncertainty specific to visual word recognition (e.g., SERIOL model, Whitney, 2001; Open-bigram model, Grainger & van Heuven, 2003). Whilst it is important to acknowledge that various accounts of letter position coding do exist, distinguishing between these accounts is not paramount to the work reported in this thesis. Therefore, when using the terminology ‘letter position coding’, I make no assumptions in regards to the specificities of how letter position is coded – only that the mechanisms underlying letter position coding are distinct from those underlying letter identity coding.

Whether or not letter position coding changes across development has been subject to debate in recent years. The evidence to date is mixed. Whilst some studies have reported that adults code letter position more precisely than children (e.g., Acha & Perea, 2008; Castles, Davis, Cavalot, & Forster, 2007; Perea & Estevez, 2008), others report no such difference (Paterson, McGowan, & Jordan, 2014). Studies reporting developmental changes across the primary school years (approximately ages 6-12) have also produced conflicting findings: some studies have reported a trend towards older children processing letter position more precisely than younger children (Acha & Perea, 2008; Castles, Davis, Cavalot & Forster, 2007), whilst others have reported that letter position is coded less precisely (or more ‘coarsely’) in older children than in younger children (Ziegler, Bertrand, Lété, & Grainger, 2014).

One possible reason for the confusion within the literature is that the baseline condition typically used to calculate the impact of the letter position manipulation, is created by manipulating the letter identities within the item. For example, items where two letter positions are transposed (such as *jugde*) are typically compared to items where two letter identities are substituted (such as *jupte*), to create a ‘letter position effect’. Considering the overwhelming amount of evidence suggesting that the mechanisms

underlying letter position and identity coding are distinct, it would not be inconceivable to hypothesise that letter position and identity coding may follow different developmental trajectories. If this is the case, then measuring the influence of the letter position manipulation against a baseline that manipulates letter identity has potential to lead to spurious results.

In light of the mixed findings within the literature, as well as the potential conflation of letter position and identity effects in previous studies, **Chapter 2** in this thesis reports a study that was designed to track the development of letter position coding in children (ages 7-12 years) and adults – independently of letter identity effects.

The Orthographic Input Lexicon

Whilst most studies investigating letter position effects focus on how letter position is coded during the early processes of orthographic-visual analysis, in this thesis I argue that the orthographic input lexicon, as well as its complex interaction with the orthographic-visual analyser, is also critical to understanding how letter position is processed across development.

Based on the interactive activation framework (McClelland & Rumelhart, 1981), the dual-route model assumes that the presentation of a written word (e.g., *form*) feeds forward activation to the matching orthographic representation for that word, as well as orthographic representations for other visually similar words (e.g., *form*, *firm*, *farm*, *fort* and *from*), whilst simultaneously inhibiting words that are visually dissimilar to the input (e.g., *pale*, *save*, *give*). The activated orthographic representations compete within the lexicon before one of the representations (typically the best match to the input) reaches the required threshold of activation needed to inhibit its neighbours and enable successful word recognition. Selection of the best candidate is facilitated by excitatory feedback of information from the orthographic input lexicon to the orthographic-visual analyser.

It has been suggested that structural changes occurring within the orthographic

input lexicon across development drive changes in how letter position is coded (Grainger et al., 2012; Grainger & Ziegler, 2011; Castles et al., 2007; Ziegler et al., 2014). For example, according to the lexical tuning hypothesis, the visual word recognition system codes letter position relatively coarsely during the early stages of reading acquisition, such that *jugde* will frequently be misperceived as the word JUDGE, or *slime* as SMILE (Castles et al., 2007). As a reader's sight word vocabulary grows, the visual word recognition system must tighten its input criterion to minimize confusion between visually similar words within the lexicon. As a result, readers with a large sight word vocabulary are less likely to misperceive *jugde* as JUDGE or *slime* as SMILE than those with a smaller sight word vocabulary (Castles et al., 2007).

However, an alternative interpretation of the reported changes in letter position effects across development is that these changes are driven by a general maturation of the visual system. Some models of visual word recognition suggest that letter position effects are a reflection of the perceptual ambiguities inherent to visual object recognition, and are hence not specific to reading (e.g., Overlap model, Gomez et al., 2008; Bayesian Reading, Norris et al., 2010). Following this logic, changes in letter position effects across reading development could reflect a reduction in noise or uncertainty to the visual system – rather than changes occurring within the lexicon itself.

Chapter 3 and **4** explores the role of the orthographic input lexicon in letter position development, independently of maturation effects. In **Chapter 3**, I investigate the influence of lexical skills on letter position processing in University students, following the assumption that the relationship between lexical skill and age is likely to be far weaker in skilled adult readers than in children still undergoing reading instruction. In **Chapter 4**, I develop a novel variant of the popular Reicher-Wheeler task (Reicher, 1969; Wheeler, 1970) in order to investigate the influence of lexical development on letter position processing in children and adults. The task required participants to report the identity of a

letter at a specified position within three lexical contexts: anagram words (e.g., *form* – which has the anagram partner *from*), pseudowords (e.g., *pilf* – *plif*) and illegal nonwords (e.g., *ftkl* – *fttl*). Since maturation effects will affect words, pseudowords, and illegal nonwords similarly, the task can be used to investigate the influence of lexical development on letter position processing (e.g., by comparing performance for words to pseudowords), independently of perceptual changes that may be occurring within the visual system.

In this thesis I also explore the potential role of the orthographic input lexicon in letter position dyslexia. One possibility is that the excessive letter position errors made by children with developmental letter position dyslexia are caused by an elevated tendency to make ‘lexical guesses’ due to an impoverished orthographic input lexicon. For example, a child with letter position dyslexia might not have an orthographic representation for the word *slime* within their lexicon. Therefore, when the orthographic representation for the word *slime* cannot be retrieved upon presentation of the word, a lexical guessing strategy is adopted based on the orthographic representations that are partially activated, resulting in the child misreading *slime* for a word that is visually similar to it, such as “smile”. This hypothesis was tested in a multiple single-case study reported in **Chapter 5**, where the locus of impairment in three children with developmental letter position dyslexia is systematically investigated.

The Phonological Output Buffer

Most studies looking at letter position effects in developing and skilled readers disregard the role of the phonological output buffer in letter position processing. This is likely because most of the studies to date have used tasks that do not require spoken output, and hence do not implicate the phonological output buffer. However, it is possible that the phonological output buffer plays a key role in influencing letter position effects in studies that use reading aloud tasks to explore letter position processing (e.g., Kohnen &

Castles, 2013; Paterson et al., 2014; Perea & Estevez, 2008). Indeed, it is theoretically possible that the word *pat* may be misread as “apt” because the phonemes /p/ and /a/ are confused as the phonological code is being prepared for pronunciation within the phonological output buffer.

The role that the phonological output buffer plays in letter position effects is particularly relevant when considering the locus of impairment in letter position dyslexia. Many researchers contend that dyslexia is caused by an inability to represent, store and retrieve speech sounds (Ramus, 2003; Snowling, 1998; Snowling, 2001; Stanovich, 1988). Following this logic, it is possible that the elevated tendency for children with letter position dyslexia to make letter position errors is caused by a phonological output buffer deficit specific to the assembling of phonemes in their correct order. The aim of the study reported in **Chapter 5** of this thesis is to test a phonological deficit account of letter position dyslexia, and compare this account with other hypothetical deficits, such as an impairment to the orthographic-visual analyser and/or the orthographic input lexicon.

Outline of Thesis

The aim of this thesis is to investigate both typical and atypical development of letter position processing. By systematically investigating all mechanisms thought to be implicated in letter position development, rather than focusing solely on letter position encoding, I hoped to resolve some of the ambiguities within the developmental literature.

Chapter 2 of this thesis presents a study mapping the developmental trajectory of letter position processing in children learning to read (ages 7-12 years) as well as skilled adult readers. The aim of the study was to improve on previous research by disentangling letter position effects from letter identity effects. By doing so, I hoped to find a cleaner pattern of results than has been reported in previous research.

Chapter 3 and 4 present two studies designed to test whether reported changes in letter position coding across development are driven by the development of lexical skills,

rather than maturation effects associated with age. In **Chapter 3**, I investigate whether lexical skills in University students influence the magnitude of the letter position effect, and in **Chapter 4**, I develop a task that enables the influence of lexical skills on letter position coding across development to be investigated independently of maturation effects.

Chapter 5 adopts a multiple single-case study design to investigate whether the excessive letter position errors made by children with letter position dyslexia are caused by an impairment to the phonological output buffer, orthographic input lexicon, and/or the orthographic-visual analyser.

Chapter 6 brings together the core themes of the work reported in this thesis, and considers the implications for past and future studies investigating the development of letter position processing.

References

- Acha, J., & Perea, M. (2008). The effects of length and transposed-letter similarity in lexical decision: Evidence with beginning, intermediate, and adult readers. *British Journal of Psychology*, 99, 245-264. doi: 10.1348/000712607X224478
- Andrews, S. (1996). Lexical retrieval and selection processes: Effects of transposed-letter confusability. *Journal of Memory and Language*, 35(6), 775-800.
doi:10.1006/jmla.1996.0040
- Andrews, S., & Lo, S. (2012). Not all skilled readers have cracked the code: individual differences in masked form priming. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 38(1), 152-163. doi: 10.1037/a0024953
- Castles, A., Bates, T., & Coltheart, M. (2006). John Marshall and the developmental dyslexias. *Aphasiology*, 20(9), 871-892. doi:10.1080/02687030600738952
- Castles, A., Davis, C., Cavalot, P., & Forster, K. (2007). Tracking the acquisition of orthographic skills in developing readers: Masked priming effects. *Journal of Experimental Child Psychology*, 97, 165-182. doi:10.1016/j.jecp.2007.01.006
- 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
- Davis, C. J. (2010). The spatial coding model of visual word recognition. *Psychological Review*, 117(3), 713-758. doi: 10.1037/a0019738
- Forster, K. I., Davis, C., Shoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology*, 39, 211-251.
- Friedmann, N., Dotan, D., and Rahamim, E. (2010). Is the visual analyzer orthographic-specific? Reading words and numbers in letter position dyslexia. *Cortex*, 46(8), 982-1004. doi:10.1016/j.cortex.2009.08.007

- Friedmann, N., and Haddad-Hanna, M. (2012). Letter position dyslexia in Arabic: From form to position. *Behavioural Neuropsychology* 25, 193-203, doi: 10.3233/BEN-2012-119004. doi:10.3233/BEN-2012-119004
- Friedmann, N., and Rahamim, E. (2007). Developmental letter position dyslexia. *Journal of Neuropsychology* 1, 201-236. doi: 10.1348/174866407X204227
- Grainger, J., & van Heuven, W. (2003). Modeling Letter Position Coding in Printed Word Perception. In P. Bonin (Eds.), *The mental lexicon*. New York: Nova Science Publishers.
- Grainger, J., & Whitney, C. (2004). Does the huamn mnid raed wrods as a wlohe? *Trends in Cognitive Sciences*, 8(2), 58-59. doi:10.1016/j.tics.2003.11.006
- Grainger, J., & Ziegler., J. C. (2011). A dual-route approach to orthographic processing. *Frontiers in Psychology*, 2(54), 1-13, doi: 10.3389/fpsyg.2011.00054
- Gomez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: a model of letter position coding. *Psychological Review*, 115(3), 577. doi: 10.1037/a0012667
- Kezilas, Y., Kohnen, S., McKague, M., Castles, A. (2014). The locus of impairment in developmental letter position dyslexia. *Frontiers in Human Neuroscience*, 8(356), 1-14. doi: 10.3389/fnhum.2014.00356
- Kohnen, S., & Castles, A. (2013). Pirates at parties: Letter position processing in developing readers. *Journal of Experimental Child Psychology*, 50(14), 3681-3692. doi: <http://dx.doi.org/10.1016/j.jecp.2012.08.011>
- Kohnen, S., Nickels, L., Castles, A., Friedmann, N., McArthur, G. (2012). When ‘slime’ becomes ‘smile’: developmental letter position dyslexia in English. *Neuropsychologia*, 50(14), 3681-3692. doi: 10.1016/j.neuropsychologia.2012.07.016
- Lee, C. H., Taft, M. (2009). Are onsets and codas important in processing letter position? A comparison of TL effects in English and Korean. *Journal of Memory and*

- Language*, 60(4), 530-542. doi:10.1016/j.jml.2009.01.002
- Lee, C. H., & Taft, M. (2011). Subsyllabic structure reflected in letter confusability effects in Korean word recognition. *Psychonomic Bulletin & Review*, 18(1), 129-134. doi: 10.3758/s13423-010-0028-y
- Lupker, S. J., & Davis, C. J. (2009). Sandwich priming: a method for overcoming the limitations of masked priming by reducing lexical competitor effects. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 35(3), 618-639. doi: 10.1037/a0015278
- Lupker, S. J., Perea, M., & Davis, C. (2008). Transposed-letter effects: Consonants, vowels and letter frequency. *Language and Cognitive Processes*, 23(1), 93-116. doi: 10.1080/01690960701579714
- Marshall, J. C., (1984). Toward a rational taxonomy of the developmental dyslexias. In R. N. Malatesha & H. A. Whitaker (Eds.), *Dyslexia: A global issue* (pp. 45-58). The Hague, the Netherlands: Martinus Nijhoff.
- McClelland, J. L., Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review*, 88, 375-407
- Norris, D. (2006). The Bayesian Reader: Explaining word recognition as an optimal Bayesian decision process. *Psychological Review*, 113(2), 327-357. doi: <http://dx.doi.org/10.1037/0033-295X.113.2.327>
- Norris, D., Kinoshita, S., & Casteren, M. (2010). A stimulus sampling theory of letter identity and order. *Journal of Memory and Language*, 62(3), 254-271. doi: 10.1016/j.jml.2009.11.002
- Paterson, K. B., Read, J., McGowan, V. A., Jordan, T. R. (2014). Children and adults both see ‘pirates’ in ‘parties’: letter-position effects for developing readers and skilled adult readers. *Developmental Science*, 18(2), 1-9. doi: 10.1111/desc.12222

- 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. doi: 10.1080/09541440701306941
- Perea, M., & Lupker, S. J. (2003). Transposed-letter confusability effects in masked form priming. In S. Kinoshita and S. J. Lupker (Eds.), *Masked priming: State of the art*. Hove, UK: Psychology Press.
- 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. doi:10.1016/j.jml.2004.05.005
- Pritchard, S., Coltheart, M., Marinus, E., & Castles, A. (submitted, 2015). A computational model of the self-teaching hypothesis based on the dual-route cascaded model of reading.
- Ramus, F. (2003). Developmental dyslexia: specific phonological deficit or general sensorimotor dysfunction? *Current Opinion in Neurobiology*, 13(2), 212-218. doi:10.1016/S0959-4388(03)00035-7
- Rayner, K., White, S. J., Johnson, R. L., & Liversedge, S. P. (2006). Reading words with jumbled letters: There is a cost. *Psychological Science*, 17, 192-193. doi: 10.1111/j.1467-9280.2006.01684.x
- Reicher, G. M. (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology*, 81, 275-280
- Seidenberg, M. D., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review*, 96(4), 523-568.
- Snowling, M. (1998). Dyslexia as a phonological deficit: Evidence and implications. *Child and Adolescent Mental Health*, 3(1), 4-11, doi: 10.1111/1475-3588.00201
- Snowling, M. (2001). From language to reading and dyslexia. *Dyslexia*, 7(1), 37-46. doi: 10.1002/dys.185

- Stanovich, K. E. (1988). Explaining the differences between dyslexia and the garden-variety poor reader. The phonological-core variable-difference model. *Journal of Learning Disabilities*, 21(10), 590-604. doi: 10.1177/002221948802101003
- Wheeler, D. D. (1970). Processes in word recognition. *Cognitive Psychology*, 1, 59-85. doi: [http://dx.doi.org/10.1016/0010-0285\(70\)90005-8](http://dx.doi.org/10.1016/0010-0285(70)90005-8)
- Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review*, 8(2), 221-243.
- Ziegler, J. C., Bertrand, D., Lété, B., & Grainger, J. (2014). Orthographic and phonological contributions to reading development: Tracking developmental trajectories using masked priming. *Developmental Psychology*, 50(4), 1026-1036. doi: 10.1037/a0035187
- 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: <http://dx.doi.org/10.1037/0096-1523.24.4.113>

Chapter 2

Disentangling the Developmental Trajectories of Letter Position and Letter Identity Coding Using Masked Priming

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Abstract

Reported findings regarding the developmental trajectory of the masked transposed-letter (TL) priming effect are mixed. One factor that may be contributing to the discrepancies within the literature is the two-substituted-letter (2SL) and the all-letters-different (ALD) baseline primes typically used to measure the TL priming effect. The 2SL and ALD prime are created by replacing the letter identities of either two letters (for the 2SL, e.g., lidfen-LISTEN) or all letters (for the ALD prime, e.g., rodgup-LISTEN) in the target, whereas the TL prime (e.g., litsen – LISTEN) shares all letter identities with the target. A change in the TL priming effect across development may therefore be confounded by a change in sensitivity to letter identity manipulations. A baseline prime that obviates this confound is the identity prime (ID; e.g., listen-LISTEN) because, like the TL prime, the identity prime shares all letters with the target. The aim of the present study was to disentangle the development of letter position from letter identity effects by investigating the cost of the TL, 2SL and ALD manipulations relative to the ID prime in children (aged 7-12 years) and adults. Responses to targets preceded by a TL, 2SL and ALD prime were slower than those preceded by an ID prime, and all three cost effects increased across development. These findings provide support for the lexical tuning hypothesis, and advocate the use of the ID prime in developmental studies as a baseline to measure letter position effects against, independently of letter identity.

Disentangling the Developmental Trajectories of Letter Position and Letter Identity Coding Using Masked Priming

Introduction

While the skilled adult reading system is typically sensitive enough to distinguish between anagrammatic words such as *pat*, *tap* and *apt*, it is also remarkably flexible, enabling these scrambled words to be comprehended with apparently little cognitive effort (Rayner, White, Johnson, & Liversedge, 2006). Clear evidence for flexible letter position coding comes from studies with skilled adult readers showing that responses to targets preceded by a masked transposed-letter nonword prime (e.g., *litsen* – LISTEN) are faster and more accurate than when preceded by a control prime (e.g., *lidfen* – LISTEN; Kinoshita, Castles, & Davis, 2009; Lupker & Davis, 2009; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2003; Perea & Lupker, 2004).

A critical unresolved question is whether or not flexible letter position coding is a stable feature of the reading system, or whether it changes across development. Developmental studies using the masked priming paradigm have produced conflicting findings – whilst some studies seem to indicate that letter position coding becomes more precise or ‘fine-tuned’ as the system matures (Acha & Perea, 2008; Castles, Davis, Cavalot, & Forster, 2007), others indicate that letter position is coded less precisely or more ‘coarsely’ in older readers (Grainger & Ziegler, 2011; Ziegler, Bertrand, Lété, & Grainger, 2014). One crucial aspect in which these studies vary is in the choice of baseline prime used to calculate the priming effect. In the present study we investigate whether the TL priming effect changes across development, and if so, whether this change is contingent on the type of baseline prime used to measure the effect.

The two baseline primes most commonly used in the masked priming literature are the (1) double-substituted-letter (2SL) prime (e.g., *lidfen* – LISTEN), formed by substituting two letters in the same positions as the transposed letters in the TL prime (e.g.,

Lupker, Perea, & Davis, 2008; Perea & Lupker, 2003; Perea & Lupker, 2004), and (2) the all-letters-different (ALD) prime (e.g., rodgup - LISTEN), formed by substituting all letters in the target (e.g., Andrews & Lo, 2012; Kinoshita et al., 2009). There is an implicit assumption within the literature that these baselines provide an equivalent reference point against which to measure the effect of the TL prime. As such, the facilitatory TL priming effects reported in these studies have been interpreted similarly, with larger facilitatory effects of the TL prime relative to the baseline indicating greater flexibility or tolerance within the visual word recognition system for manipulations of letter position.

However, studies with skilled adult readers including both baseline conditions indicate that a degree of caution should be used when comparing TL effects measured using a 2SL baseline to those using an ALD baseline. A recent mega study by Adelman, Johnson, McCormick, McKague, Kinoshita, Bowers et al. (2014) reported that the TL priming effect in skilled adult readers was smaller when measured against the 2SL prime compared to when the effect was measured against the ALD prime (see also Humphreys, Quinlan, & Evett, 1990, Experiment 2b for a similar finding using the fourfield priming paradigm). This finding suggests that skilled readers are sensitive to the number of letter identities in the target that have been replaced to form the baseline prime – a baseline that replaces all letters in the target (ALD) produces a larger priming effect than a baseline that replaces only two letters (2SL).

The visual word recognition system's sensitivity to letter identity manipulations not only makes it difficult to draw comparisons between studies using different baselines, but brings into question the very foundations of the TL priming effect. It is unclear whether the TL effect, when measured against the ALD, is the result of flexible letter position coding, or is due to the fact that the TL prime shares all letter identities with the target whereas the ALD prime does not. The TL priming effect relative to the 2SL prime has similar interpretative issues – the priming effect may be driven by the letter position manipulation

in the TL prime, or by the letter identity manipulation in the 2SL prime.

Disentangling letter position from letter identity effects becomes critical when considering the TL priming effect within a developmental context. This is because a reader's sensitivity to letter identity manipulations has been reported to change as reading develops (e.g., Castles et al., 2007; Lété & Fayol, 2013). For example, Castles et al. (2007) found that grade 3 readers responded more quickly when targets in a lexical decision task were preceded by a single letter substitution prime (e.g., rlay – PLAY) than when they were preceded by an ALD prime. When the same children were retested in grade 5, they no longer showed the substitution priming effect, nor did a separate sample of skilled adult readers. Castles et al. (2007) interpreted their results within the context of the lexical tuning hypothesis. According to this account, the visual word recognition system is tolerant to the letter identity manipulation within the substitution prime early in development, resulting in a facilitatory priming effect. As a reader's sight word vocabulary grows, the visual word recognition system tightens its input criterion to minimize potential confusion between orthographic neighbours (e.g., *play* has neighbours including *pray*, *ploy*, *plat*, and *slay*). As a result of lexical tuning, a prime that differs from the target by a single letter does not benefit target processing for older readers – at least for words with many neighbours (Forster, Davis, Schoknecht, & Carter, 1987; Forster & Taft, 1994).

Given the potential for conflating the developmental changes in letter position coding with changes in letter identity coding, it is perhaps not surprising that studies attempting to map the developmental trajectory of TL priming have produced conflicting results. Whilst some studies have found that the facilitatory TL priming effect *decreases* across development relative to a 2SL (Acha & Perea, 2008) or an ALD baseline (Castles et al., 2007), others have reported priming to *increase* (relative to 2SL: Ziegler et al., 2014; relative to ALD: Lété & Fayol, 2013). These mixed findings have been interpreted within the context of two somewhat contradictory theories of letter position development. Reports

of a decrease in TL priming across development have been interpreted as reflecting a refinement of the precision of letter position coding over development, in line with the lexical tuning hypothesis outlined above. As is the case for letter identity coding, the lexical tuning hypothesis posits that the visual word recognition system becomes more sensitive to the position of letters within words as reading develops, in order to avoid confusion between visually similar words (e.g., *pat*, *tap*, *apt*). In contrast, reports of larger TL priming effects for older readers have been interpreted to occur due to a developmental transition from serial to parallel letter processing (Grainger & Ziegler, 2011). Following this account, beginning readers adopt a sequential grapheme-to-phoneme phonological recoding strategy, which is highly sensitive to the position of letters within words. As orthographic knowledge develops, the sequential strategy is replaced by a specialised parallel letter processing system, which prioritises rapid word retrieval over precise letter position encoding, reflecting an increasingly coarse encoding of letter position information as reading skill increases.

Resolving the mixed findings within the developmental literature, and discriminating between these conflicting accounts of letter position development, requires that the TL priming effect be measured against a baseline that does not confound letter position with letter identity effects. As noted by Kinoshita et al. (2009), one way to achieve an unambiguous measure of the effect of the transposition manipulation is to compare the TL prime to an identity (ID) prime that is an exact match to the target (e.g., listen – LISTEN). The advantage of this comparison is that both the TL and ID primes share all letter identities with the target and differ only in the position of the letters. Measured this way, the magnitude of the difference between the TL and ID conditions reflects the cost of the transposition manipulation, with larger TL priming effects indexing greater precision in the coding of letter position information (i.e., less tolerance to the TL manipulation), reversing the facilitation logic of the more standard comparison of the TL prime against

substitution controls.

Using the ID-TL comparison in a study with adult readers, Kinoshita et al. (2009) showed a small but significant TL cost effect, which was modulated by the neighbourhood density of the targets. Contrary to the lexical tuning account, words with relatively more orthographic neighbours (high-N words) showed a smaller TL priming cost than words with relatively few neighbours (low-N words). Neighbourhood density could be considered something of a proxy for reading development, with high-N words reflecting the lexicon of a reader with a large sight word vocabulary. Following this logic, the finding that high-N words showed a smaller TL cost than low-N words provides indirect support for the idea that letter position may be coded more coarsely in skilled than in novice readers.

However, whilst neighbourhood density effects provide useful hints in regards to how the TL cost effect might change across reading development, extrapolating from adult data is not ideal – especially considering the mixed findings within the developmental priming literature. Rather, what is needed is a systematic investigation of the TL priming effect from both the conventional TL advantage perspective (i.e., TL prime compared to either the 2SL or ALD baseline) and the TL cost perspective (i.e., TL prime compared to the ID baseline), in order to resolve the mixed findings within the literature and to provide a strong test for the two contrasting theories of letter position development.

The aim of the present study was to investigate the development of letter position coding using the masked priming technique. Four developmental groups were included in the study – children in early primary school (grade 2 and 3), middle primary school (grade 4), late primary school (grade 5 and 6) and University students. To enable comparison to previous work, we first report the TL priming effect as measured against the traditional 2SL and ALD conditions. Considering our proposition that measuring the TL priming effect in this way conflates letter position with letter identity effects, we had no clear predictions regarding the development of these effects. To disentangle letter position from

letter identity effects, we measured the cost of transposing two letters (TL prime), substituting two letters (2SL prime) and substituting all letters (ALD prime) relative to the ID prime. Following previous research (e.g., Acha & Perea, 2008; Castles et al., 2007; Ziegler et al., 2014) we expected all three cost effects to change across the four groups, indicating that sensitivity to letter position and identity manipulations changes across development.

Exactly how the TL priming cost changes across development (independent of letter identity effects) was of primary concern in the present study. We had two contrasting predictions. If letter position processing becomes more precise as reading develops, as suggested by Acha and Perea (2008) and Castles et al. (2007), we should observe an increase in the cost of the TL priming manipulation across development, indicating that the visual word recognition system is becoming less tolerant to manipulations of letter position. Alternatively, if letter position information is coded more coarsely with development, as suggested by Ziegler et al. (2014), we should observe a decrease in the cost of the TL priming manipulation, consistent with the hypothesis that sequential phonological recoding processes are replaced by a specialised parallel letter processing system which is relatively insensitive to the position of letters within words.

Method

Participants

Eighty-four children from grades 2 to 6 were tested during the first semester of the school year. The children were tested as part of a research holiday program at Macquarie University. Children received a small monetary reward for their participation. The adult sample consisted of 40 undergraduate students from Macquarie University who participated in the study in exchange for course credit. All participants were native speakers of English. Further information about participants is detailed in Table 1.

Table 1. N, gender, and age of participants in each grade level.

Numbers in parentheses denote the standard deviation of the mean.

Grade	N	Gender (female)	Age (years;months)
2	15	6	7;8 (0;5)
3	13	7	8;6 (0;4)
4	25	11	9;5 (0;4)
5	14	7	10;7 (0;4)
6	16	5	11;7 (0;5)
University	40	35	23;2 (8;5)

Materials

The task consisted of 72 target words and 72 target nonwords, which were 5 and 6 letters in length ($M = 5.64$, $SD = 0.48$). Target words were selected from the Oxford Wordlist (Bianco, Scull, & Ives, 2008) to be known by children in grade 1. All words except for one were also included in the Children's Printed Word Database (Masterson, Stuart, Dixon, & Lovejoy, 2003). On average, target words had a CELEX written word frequency of 259.81 per million ($SD = 351.77$), and a neighbourhood density of 2.53 ($SD = 2.86$) using Coltheart's N (Coltheart, Davelaar, Jonasson, & Besner, 1977). Each target word was paired with four primes, including, a transposed-letter (TL) prime (e.g., litsen - LISTEN), a double-substituted-letter (2SL) prime (e.g., lidfen - LISTEN), an all-letters-different (ALD) prime (e.g., rodgup - LISTEN), and an identity (ID) prime (e.g., listen - LISTEN). The TL and 2SL primes were created by changing two internal consonants within the target word. Fifty-eight of the 72 items involved changing adjacent consonants, and 14 involved changing nonadjacent consonants. The 2SL prime was matched to the TL prime by substituting letters of the target at the same letter positions that were transposed in the TL prime. To ensure comparability of the 2SL and ALD conditions, the two

substituted letters in the 2SL prime were carried over to the ALD prime in the same positions, and all remaining letters in the target were then substituted (vowels for vowels and consonants for consonants). The 2SL and ALD primes were matched as closely as possible on Coltheart's N, with most primes having no neighbours (range = 0-3). Frequency and neighbourhood density estimates were obtained using N-Watch (Davis, 2005)

Target nonwords were created by replacing at least two letters of each target word, such that target nonwords and words were matched on CV structure. Each target nonword was paired with a TL prime, a 2SL prime, an ALD prime, and an ID prime. Primes were created for the nonword targets in the same way as described above for the word targets. Stimuli are reported in the Appendix.

Procedure

The experiment was run using DMDX (Forster & Forster, 2003). The two-alternative-forced-choice responses were made using an external button box, recording response times and accuracy. On each trial, a string of hashmarks was presented for 500ms, followed by the prime in lowercase for 50ms, followed by the target. The target remained on the screen for up to 10 seconds or until the participant made a response. Participants were encouraged to respond as accurately and as quickly as possible. The experiment started with a practice block of 16 items, followed by 6 blocks of 24 items, including two buffer items at the beginning of each block, which were not included in the analysis. Children were given additional instructions using flash cards prior to the task to ensure they understood the requirements. Item presentation was randomised for each individual. Four lists of the task were created such that participants saw each target only once in a single condition.

Data Treatment

Items with response times less than 150ms or more than 4000ms were excluded

from the analysis, comprising 1.12% of the data in total. Four participants who made more than 40% errors on the task (3 in grade 2, 1 in grade 3) were excluded from the analysis. Three words and 5 nonwords that produced more than 40% errors in at least one grade level were then excluded. Incorrect responses were excluded from the RT analyses.

Because there were too few participants in some grade levels, we were unable to include grade level reliably in the analysis. We therefore grouped participants into four developmental categories: early primary schoolers (grade 2 and 3 combined, $N = 23$) middle primary schoolers (grade 4, $N = 25$), late primary schoolers (grade 5 and 6 combined, $N = 29$), and University students ($N = 40$). For ease of interpretation and comparison to previous studies, the analyses reported use these four groups to index reading development.

Inverse RTs ($1000/RT$) were used to normalise the data and reduce the impact of outliers (Ratcliff, 1993). The inverse transformed RT data by prime type and group is presented in Figure 1, and is back-transformed (larger numbers reflecting slower responses) for ease of interpretation. To enable comparison to previous studies using untransformed RTs rather than inverse RTs, the untransformed data is reported in Table 2, and the priming effects based on the transformed data in Table 3.

Accuracy data and nonword data were not analysed as we had no clear predictions in regards to these effects. Nevertheless the accuracy and nonword data are included in Table 2 for completeness. Observation of the RT data relative to the accuracy data revealed no evidence for a speed-accuracy trade off.

Linear mixed effects modelling, as implemented in lme4 package (Bates, Maechler, Bolker, & Walker, 2014) formed the main analyses. Five separate analyses were performed for each priming effect of interest (TL vs ALD, TL vs 2SL, TL vs ID, TL vs 2SL, ALD vs ID). For each analysis, we used competitive model testing to first settle on a general model, before undertaking more detailed analyses. Three models were considered: (1) a

model including the main effect of condition, (2) a model including the main effect of condition and group, and (3) a model including the main effect of condition and group, as well as the interaction between the two. Intercepts were allowed to vary by subjects and items. Models were compared pair-wise in order of complexity. Model (1) was compared to an intercept-only model.

Follow-up contrasts are based on the best fitting model – defined for the present purposes as the most complex model that provided a significantly better fit to the data than the simpler model it was compared to. Where Model 3 provided the best fit to the data, the interaction between prime and group was followed up with a one-way ANOVA trend analysis (based on the subject and item data separately) to investigate the change in the priming effect across the developmental groups.

Results

TL Priming Measured Against 2SL Baseline

The best fitting model included a main effect of prime and a main effect of group, $\chi^2(3) = 120.76, p < .0001$. The model including the interaction term did not significantly improve the fit to the data, $\chi^2(3) = 1.39, p = .71$). Words preceded by a TL prime were responded to faster than words preceded by a 2SL prime, $t = 4.22, p < .0001$, and older participants were faster to respond than younger participants (t for each group compared to early primary $< .01$).

TL Priming Measured Against ALD Baseline

The best fitting model included a main effect of prime and a main effect of group, $\chi^2(3) = 118, p < .0001$. Including the interaction term did not significantly improve the fit to the data, $\chi^2(3) = 1.35, p = .72$). Words preceded by a TL prime were responded to faster than words preceded by an ALD prime, $t = 6.19, p < .0001$, and older participants responded faster to words than younger participants (t for each group compared to early primary $< .01$).

TL priming measured against ID baseline

The best fitting model included the interaction between prime and group, $\chi^2(3) = 13.89, p < .01$. The interaction reflected slower responses for targets preceded by a TL prime relative to those preceded by an ID prime for all groups, except early primary (Early $t = .08, p = .94$; Middle $t = 2.08, p < .05$; Late $t = 2.68, p < .01$; University $t = 6.07, p < .001$). Furthermore, a trend analysis using a one-way ANOVA revealed a significant linear increase in the priming cost across the four groups, $F_1(1,114) = 10.64, p < .01$; $F_2(1,272) = 6.33, p < .05$. The quadratic and cubic terms did not reach significance, all $F_s < 1.05$.

2SL Priming Measured Against ID Baseline

The model including the interaction between prime and group provided a marginally better fit to the data than the model including the main effects of prime and group only, $\chi^2(3) = 7.19, p < .07$. Follow-up contrasts were based on this model, despite the interaction not reaching significance at the .05 alpha level. All groups were slower to respond to targets preceded by a 2SL prime than targets preceded by an ID prime (Early $t = 2.53, p < .05$; Middle $t = 4.27, p < .0001$; Late $t = 4.79, p < .0001$; University $t = 7.92, p < .0001$). A one-way ANOVA trend analysis revealed a linear increase in the priming cost across the four groups, which was significant by subjects, $F_1(1,114) = 7.78, p < .01$, and marginal by items, $F_2(1,272) = 3.81, p < .06$. The quadratic and cubic terms were not significant in either analysis, both $F_s < 1$.

ALD Priming Measured Against ID Baseline

The best fitting model included the interaction between prime and group, $\chi^2(3) = 18.89, p < .001$. All groups made slower responses to targets preceded by an ALD prime relative to targets preceded by an ID prime (Early $t = 2.62, p < .01$, Middle $t = 3.85, p < .001$; Late $t = 5.80, p < .0001$; University $t = 10.25, p < .0001$). A one-way ANOVA trend analysis revealed a significant linear increase in the priming cost across the four groups, $F_1(1,114) = 16.22, p < .001$; $F_2(1,272) = 10.90, p < .01$. The quadratic and cubic

terms were not significant in either analysis, all $F_s < 1$.

In sum, measuring the TL priming effect against the traditional baselines (2SL and ALD) revealed a significant facilitatory priming effect that remained stable across development. In contrast, when the TL priming effect was measured as a cost relative to the ID prime, the effect changed significantly across the three groups. Specifically, the TL cost increased linearly with age, suggesting that older readers are less tolerant to manipulations of letter position. A similar pattern of results was observed when the 2SL and ALD prime were compared to the ID prime, suggesting that readers also become less tolerant to letter identity manipulations with age.

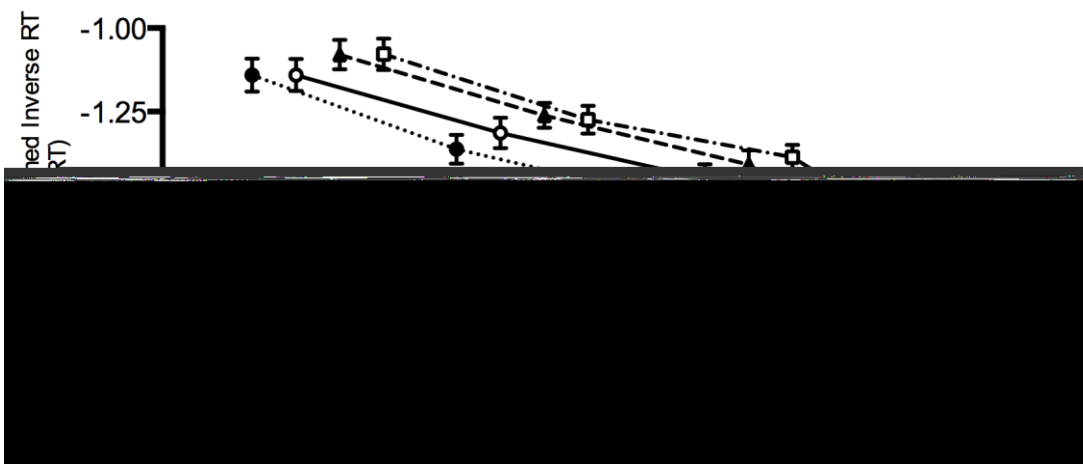


Figure 1. Mean inverse RTs by prime type for early primary schoolers, middle primary schoolers, late primary schoolers, and University students based on subject data. Mean inverse RTs have been back-transformed for ease of interpretation. Smaller inverse RTs indicate faster response times. Error bars denote the standard error of the mean.

Table 2. Accuracy (%) and RT (ms) for words and nonwords by prime type and developmental group. Numbers in parentheses denote the standard deviation of the mean.

	Word				Nonword			
	ID	TL	2SL	ALD	ID	TL	2SL	ALD
Early primary	Accuracy (%)	89.15 (6.58)	90.03 (9.06)	89.08 (10.36)	86.53 (13.49)	87.52 (17.64)	84.61 (16.97)	86.59 (15.39)
	Raw RT (ms)	1050.31 (343.80)	1084.77 (369.76)	1102.07 (386.12)	1271.65 (432.43)	1276.36 (489.63)	1226.86 (402.24)	1300.25 (466.09)
Middle primary	Accuracy (%)	92.12 (8.73)	94.59 (6.14)	91.84 (6.56)	89.81 (11.42)	91.91 (8.01)	89.08 (9.89)	90.88 (9.79)
	Raw RT (ms)	811.92 (153.81)	857.95 (207.26)	874.02 (169.38)	1024.27 (252.71)	1023.16 (219.32)	992.19 (252.40)	1009.85 (256.48)
Late primary	Accuracy (%)	93.26 (6.30)	94.06 (7.03)	93.45 (5.84)	91.91 (8.34)	90.33 (12.56)	92.59 (7.66)	93.51 (6.65)
	Raw RT (ms)	739.36 (166.11)	764.92 (155.75)	799.45 (168.53)	887.65 (183.40)	930.88 (248.90)	890.23 (192.13)	899.12 (212.44)
University	Accuracy (%)	98.41 (2.62)	96.22 (4.83)	96.10 (4.95)	93.93 (9.77)	96.54 (8.16)	95.67 (7.57)	95.99 (5.83)
	Raw RT (ms)	538.25 (85.26)	570.11 (82.42)	591.96 (77.16)	704.09 (226.19)	696.47 (225.79)	699.83 (222.37)	724.48 (196.73)

Table 3. Untransformed RT priming effects (ms) for each group. Numbers in parentheses denote the standard deviation of the mean.

	TL-2SL	TL-ALD	ID-TL	ID-2SL	ID-ALD
Early primary	-47.64 (147.33)	-64.94 (156.93)	13.18 (113.60)	-34.46 (123.39)	-51.76 (164.40)
Middle primary	-18.91 (102.60)	-16.07 (85.15)	-46.03 (101.57)	-64.94 (96.39)	-62.10 (89.91)
Late primary	-39.89 (111.46)	-34.53 (89.54)	-25.56 (75.97)	-65.45 (117.55)	-60.09 (90.16)
University	-4.99 (43.91)	-21.85 (51.05)	-31.86 (49.19)	-36.86 (29.48)	-53.71 (47.00)

Discussion

The present study investigated whether letter position coding changes across development, and if so, in what way. To do this, we administered a masked TL priming task to students in early primary school (grade 2 and 3), middle primary school (grade 4), late primary school (grade 5 and 6), and University. Response times to target words were significantly faster when preceded by a TL prime relative to the 2SL and ALD prime conditions, and the magnitude of both effects did not change across development. Furthermore, response times were slower for words preceded by a TL, 2SL and ALD prime relative to the ID prime, and the magnitude of all three cost effects increased with development.

The finding that the TL priming effect measured against the 2SL and ALD baselines remained stable across the four groups initially appears to contradict previous reports of either a decrease (Acha & Perea, 2008; Castles et al., 2007) or an increase (Lété & Fayol, 2013; Ziegler, 2014) in the facilitatory priming effect as reading develops.

However, closer observation of the raw data in the present study reveals similarities to previous findings. Using untransformed RTs, both Acha and Perea (2008) and Castles et al. (2007), found a small decrease in the size of the TL priming effect across grade 3, 5, and University. The untransformed RT data in the present study (reported in Table 2 and 3) converge with these findings, with students in early primary school (grade 2 and 3) showing the largest priming effects (2SL baseline: 47.64ms; ALD baseline: 64.94ms), followed by students in late primary school (2SL baseline: 39.89ms; ALD baseline: 34.53ms), followed by University students (2SL baseline: -4.99; ALD baseline: -21.85).

Our findings contrast strikingly with those reported by Ziegler et al. (2014) and Lété and Fayol (2013) – both studies conducted with French readers. Using inverse transformed RTs, Ziegler et al. (2014) found a gradual increase in the TL priming effect across grades 1 to 5 relative to the 2SL baseline. Similarly, using untransformed RTs, Lété and Fayol (2013) reported significant TL priming relative to an ALD baseline for grade 5 and adult readers, but not grade 3 readers. One explanation for the discrepancy between these findings and those reported in the present study is that letter position processing develops differently for French and English readers (see Frost, 2012 for a review of cross-language differences in letter position effects). According to Lété and Fayol (2013), because the mapping of orthography onto phonology is more consistent in French than in English, French children may rely more heavily on phonological recoding than English children early in reading development. This reliance on phonological recoding means that TL priming effects emerge later in French readers than in English readers as “...their orthographic lexicon [is] less keenly tuned to orthographic processing...” (Lété & Fayol, 2013, pp. 4). This interpretation, however, does not explain why the developmental trajectory of the TL priming effect reported by Acha and Perea (2008) in Spanish – a highly transparent orthography – converges with Castles et al.’s findings (2007) in English, as well as the untransformed RT data reported in the present study.

Speculation regarding these mixed findings is limited following the finding that sensitivity to the letter identity manipulations in the 2SL and ALD prime relative to the ID prime increases across development. The finding that sensitivity to the 2SL and ALD prime relative to the ID prime increases across development not only makes it difficult to resolve the mixed findings within the literature, but calls into question the factors influencing the TL priming effect as it has been traditionally measured. We argue that disentangling letter position from letter identity effects requires measuring priming against a baseline that is matched to the TL prime on the number of letter identities it shares with the target. The TL and ID prime both share all letter identities with the target, deeming the ID prime an ideal baseline to measure the cost of the TL manipulation against (Kinoshita et al., 2009).

Approaching the TL priming effect from the perspective of a cost relative to the ID prime revealed a clear pattern of results. The TL priming cost increased across development, suggesting that flexible letter position coding becomes more refined as reading develops. This finding, as well as the finding that the 2SL and ALD cost relative to the ID prime increased across development, provides support for the lexical tuning hypothesis (Castles et al., 2007; Forster, Davis, Schoknecht, & Carter, 1987; Forster & Taft, 1994). Early in reading development, the visual word recognition system is somewhat tolerant to letter position and letter identity manipulations, such that the cost of transposing two letters (TL prime), substituting two letters (2SL prime), or substituting all letters (ALD prime) in the target is small relative to the ID prime. As a reader's sight word vocabulary develops, the system tightens its input criterion to minimize competition between visually similar words, resulting in less tolerance (i.e., a larger cost) to the letter position and identity manipulations within the TL, 2SL and ALD primes. Whether or not the developmental trajectory of these cost effects is similar in more transparent orthographies, such as French and Spanish, remains to be seen. Further investigations also need to be

undertaken to test whether the pattern of results reported here is driven by growth in sight word vocabulary, as proposed by the lexical tuning hypothesis. In any case, the findings from the present study strongly suggest that investigating form priming from a cost perspective is the essential next step to getting to the bottom of the mixed findings within the literature.

In advocating the use of the ID comparison we do not wish to suggest the abandonment of the 2SL and ALD baseline conditions in developmental studies. The 2SL and ALD conditions play a critical role in determining how tolerant the visual word recognition system is to manipulations of letter position. For example, considered in isolation, the relatively large TL cost (measured against the ID prime) in the adult sample suggests that the skilled visual word recognition system is intolerant to letter position manipulations. Measuring the TL priming effect against the ID, 2SL and ALD conditions tells a more complete story: there is certainly a cost associated with the letter position manipulation, but the visual word recognition system is by no means intolerant to it, as is evidenced by the significant facilitatory TL priming effects relative to the 2SL and ALD prime.

Finally, it is important to note that the implications of these findings extend beyond the masked priming paradigm. A 2SL baseline condition is also typically used in tasks such as TL pseudoword naming (e.g., Perea & Estevez, 2008) and un-primed lexical decision (e.g., Grainger, Lété, Bertrand, Dufau, & Ziegler, 2012), where participants are required to make responses to TL and 2SL items (e.g., *jugde* vs *jupte*). The findings from the present study imply that appropriate baseline comparisons that do not conflate letter position with letter identity effects may be required for all tasks designed to investigate letter position effects across development.

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References

- Acha, J., & Perea, M. (2008). The effects of length and transposed-letter similarity in lexical decision: Evidence with beginning, intermediate, and adult readers. *British Journal of Psychology*, 99, 245-264. doi: 10.1348/000712607X224478
- Adelman, J. S., Johnson, R. L., McComick, S. F., McKague, M., Kinoshita, S., Bowers, J. S., ... & Davis, C. J. (2014). A behavioural database for masked form priming. *Behaviour Research Methods*, 46(4), 1052-1067. doi: 10.3758/s13428-013-0442-y
- Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*. 67, 1-48.
doi:10.18637/jss.v067.i01.
- Bianco, J. L., Scull, J., & Ives, D. (2008). The Words Children Write: Research Summary of the Oxford Wordlist Summary. Retrieved from:
<http://www.education.vic.gov.au/Documents/school/teachers/teachingresources/discipline/english/oxfordwordlist.pdf>
- Castles, A., Davis, C., Cavalot, P., & Forster, K. (2007). Tracking the acquisition of orthographic skills in developing readers: Masked priming effects. *Journal of Experimental Child Psychology*, 97, 165-182. doi:10.1016/j.jecp.2007.01.006
- Coltheart, M., Davelaar, E., Jonasson, J. T., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Eds.), *Attention and Performance VI*. Hillsdale, NJ: Erlbaum.
- Davis, C. J. (2005). N-Watch: A program for deriving neighbourhood size and other psycholinguistics statistics. *Behaviour Research Methods*, 37(1), 65-70. doi: 10.3758/BF03206399
- Forster, K. I., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology*, 39, 211-251.
- Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with

millisecond accuracy. *Behavior Research Methods, Instruments, & Computers*, 35(1), 116-124.

Forster, K. I., & Taft, M. (1994). Bodies, antibodies, and neighbourhood density effects in masked form priming. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 20(4), 844-863. doi: 10.1037/0278-7393.20.4.844

Frost, R. (2012). Towards a universal model of reading. *Behavioural and Brain Sciences*, 35(5), 263-279. doi: 10.1017/S0140525X11001841

Grainger, J., L  t  , B., Bertrand, D., Dufau, S., Ziegler, J. C. (2012). Evidence for multiple routes in learning to read. *Cognition*, 123, 280-292.
doi:10.1016/j.cognition.2012.01.003

Grainger, J., & Ziegler, J. C. (2011). A dual-route approach to orthographic processing. *Frontiers in Psychology*, 2(54), 1-13. doi: 10.3389/fpsyg.2011.00054

Humphreys, G. W., Evett, L. J., & Quinlan, P. T. (1990). Orthographic processing in visual word recognition. *Cognitive Psychology*, 22(4), 517-560. doi:10.1016/0010-0285(90)90012-S

Kinoshita, S., Castles, A., & Davis, C. (2009). The role of neighbourhood density in transposed-letter priming. *Language and Cognitive Processes*, 24(4), 506-526. doi: 10.1080/01690960802289213

L  t  , B., & Fayol, M. (2013). Substituted-letter and transposed-letter effects in a masked priming paradigm with French developing readers and dyslexics. *Journal of Experimental Child Psychology*, 114(1), 47-62. doi: 10.1016/j.jecp.2012.09.001

Lupker, S. J., & Davis, C. J. (2009). Sandwich priming: a method for overcoming the limitations of masked priming by reducing lexical competitor effects. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 35(3), 618-639. doi: 10.1037/a0015278

Lupker, S. J., Perea, M., & Davis, C. (2008). Transposed-letter effects: Consonants, vowels

and letter frequency. *Language and Cognitive Processes*, 23(1), 93-116. doi:
10.1080/01690960701579714

Masterson, J., Stuart, M., Dixon, M., & Lovejoy, S. (2003). *Children's Printed Word Database*. Colchester, UK: University of Essex.

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. doi: 10.1080/09541440701306941

Perea, M., & Lupker, S. J. (2003). Transposed-letter confusability effects in masked form priming. In S. Kinoshita and S. J. Lupker (Eds.), *Masked priming: State of the art*. Hove, UK: Psychology Press.

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. doi:10.1016/j.jml.2004.05.005

Ratcliff, R. (1993). Methods for dealing with reaction time outliers. *Psychological Bulletin*, 114(3), 510-532. doi:10.1037/0033-2909.114.3.510

Rayner, K., White, S. J., Johnson, R. L., & Liversedge, S. P. (2006). Reading words with jumbled letters: There is a cost. *Psychological Science*, 17, 192-193

Ziegler, J. C., Bertrand, D., Lété, B., & Grainger, J. (2014). Orthographic and phonological contributions to reading development: Tracking developmental trajectories using masked priming. *Developmental Psychology*, 50(4), 1026-1036. doi:
10.1037/a0035187

Appendix

Target words and primes

Target	ID	TL	2SL	ALD	Target	ID	TL	2SL	ALD
ATLAS*	atlas	altas	abras	ibrun	LEDGE	ledge	legde	lefre	bifro
WORMS	worms	womrs	wonbs	finbl	WHALE	whale	wlahe	wrabe	trobi
EIGHT	eight	eihgt	eispt	oaspn	LUNCH	lunch	lucnh	lubsh	kibst
CLOSE	close	csole	cmobe	vmabi	WATCH	watch	wacth	wanph	minpk
WORLD	world	wolrd	wosfd	masfv	BIRDS	birds	bidrs	bimfs	numfz
THREE	three	trhee	tlbee	slboo	FIRST	first	fisrt	ficdt	nocdm
AFTER	after	atfer	akser	ukson	CELERY*	celery	cerely	cemeby	pomibt
OWNERS	owners	onwers	ovbers	avbipz	BANGED	banged	bagned	balred	molrus
THIRTY	thirty	thitry	thikpy	slokpn	PACKET	packet	pakcet	pavbet	nivbor
TWELVE	twelve	twevle	twecke	bnicko	LOCKED	locked	lokced	lomfed	simfun
BUSHES	bushes	buhses	buvjes	movjid	LIGHTS	lights	lihgts	licfts	nocfnr
BARKED	barked	bakred	bagmed	nogmif	TRYING	trying	tyring	tlping	slposh
NUMBER	number	nubmer	nujder	bojdip	MARKET	market	makret	mafget	lofgob
WIZARD	wizard	wirazd	winapd	fonupx	MASTER	master	matser	mabler	poblin
PICKED	picked	pikced	pixsed	nexson	OPENED	opened	onaped	ogebed	ugibur
BEHIND	behind	benihd	bekigd	lukogm	TURNED	turned	tunred	tupsed	bopsik
MOTHER	mother	mohter	mopger	yupgiv	JUMPED	jumped	jupmed	jugbed	pagbin
THINGS	things	thigns	thimbs	slambr	PEOPLE	people	peolpe	peogbe	maigbu
FIFTY	fifty	fitfy	fidby	nodbl	CHASE	chase	csahe	cnaqe	dniqu
WHOLE	whole	wlohe	wnobe	snuhi	LUCKY	lucky	lukcy	lutmy	botmz
ANGRY	angry	anrgy	anwfy	ubwfl	THREW	threw	trhew	tdsew	bdsag
EARTH	earth	eatrh	eagph	oigpn	PARTY	party	patry	panby	gonbs
UNTIL*	until	utnil	ufgil	ofgep	EVERY	every	erevy	eteny	utonb
NIGHT	night	nihgt	nifct	vafcd	OTHER	other	ohter	olfer	alfud
ASKED	asked	aksed	apwed	opwib	EAGLES	eagles	ealges	eafhes	oifhuz
TYPING	typing	tpying	tlming	clmars	TWENTY	twenty	twetny	twevpy	brivpl
MEMORY	memory	meromy	mecoby	nicabp	CHURCH	church	chuchr	chubth	slibtn
KICKED	kicked	kikced	kipred	fopran	EXCEPT	except	ecxept	ebnept	abnirf
SUNDAY	sunday	sudnay	supqay	copqeb	LISTEN	listen	litsen	lidfen	rodfup
PERSON	person	pesron	peqmon	biqmud	ANIMAL	animal	aminal	atibal	utobeg
BOUGHT	bought	bouhgt	bourlt	nairld	CENTRE	centre	cetnre	cespre	mospbu
SECRET	secret	sercet	sevnet	livnob	FLYING	flying	fyling	frping	brpath
HUNGRY	hungry	hugnry	hubtry	sabtml	FAMILY	family	falimy	fagiby	dogabs
PLACES	places	pcales	phaves	thuvon	ALWAYS	always	awlays	agmays	igmudf
BEFORE	before	berofe	benole	junila	WANTED	wanted	watned	wacred	bocrul
SCHOOL	school	shcool	stmool	brneek	LITTLE	little	litlte	litbje	poddka

*Items removed from analyses due to high error rates

Appendix cont.

Target nonwords and primes

Target	ID	TL	2SL	ALD	Target	ID	TL	2SL	ALD
IMCUN	imcun	icmun	ikdun	akdob	BENGE	benge	begne	bewhe	diwho
ZORTS	zorts	zotrs	zopjs	mipjb	THAGE	thage	tgahe	tdabe	sdibu
AIPHT	aipht	aihpt	aingt	oungs	FONCH	fonch	focnh	fokph	zikpr
CRUME	crume	cmure	cbule	nboli	FOTCH*	fotch	focth	forvh	birvs
GARLD	garld	galrd	gambd	fimbn	BORFS	borfs	bofrs	bokms	nakmn
SHRIE	shrie	srhie	slnie	glnao	GORST	gorst	gosrt	gonft	danfh
OFTIR*	oftir	otfir	onbir	anbem	VILEBY	vileby	vibely	visedy	nusadt
IMTERS	imters	itmers	ivpers	avpows	LANTED	lanted	latned	lafred	bofriz
SHIMTY*	shimty	shitmy	shifry	blafrn	HUCKER	hucker	hukcer	hubser	nibsow
THELSE	thelse	thesle	thepde	fripdo	GOCHED	goched	gohced	gojred	sijral
NISHES	nishes	nihses	nipres	buprot	DOGHTS	doghts	dohgts	dovpts	javpnz
ZANGED	zanged	zagned	zaphed	kophim	BLYANG	blyang	bylang	bt pang	rtpiwb
BOMVER	bomver	bovmer	boxper	daxpid	BIRNET	birnet	binret	bifket	vafkow
WIBORD	wibord	wirobd	wipogd	mapugn	BASLED	basled	balsed	bafned	tofnir
NISHED	nished	nihsed	nirzed	farzib	OBIFED	obifed	ofibed	osihed	asuhan
BEMING	beming	benimg	bejsg	najosb	FOSNED	fosned	fonsed	fokred	bakrip
MISHOR	mishor	mihsor	miplor	kapluw	NUMLED	numled	nulmed	nugped	bigpof
PHUNGS	phungs	phugns	phubrs	clibrt	NEOSTE	neoste	neotse	neorhe	yairhu
HIDTY	hidty	hitdy	hifby	po fbs	CHELE	chele	clehe	cmebe	dmubi
WHABE	whabe	wbahe	wlane	tlino	MOCKY*	mocky	mokcy	motry	watrd
OBFRY	obfry	obr f y	obndy	alndm	SHROW	shrow	srhow	stpov	gtpam
OARSH	oarsh	oasrh	oagdh	eigdn	NARFY	narfy	nafry	nacsy	mocsb
IMTOL	imtol	itm ol	ibnol	abned	EDEBY	edeby	ebedy	enewy	onowp
BIPHT	bipht	bihpt	binkt	conkw	ASHOR	ashor	ahsor	atbor	itbaf
ANRED	anred	arned	asyed	isyof	OABLES	oables	oalbes	oacwes	iucwur
BYPONG	bypong	bpyong	bwtong	jwtash	CHONTY	chonty	chotny	chovky	slavkm
ZUMORY	zumory	zuromy	zuvopy	bavipt	SHORCH	shorch	shochr	shoklh	plaklt
WUCKER	wucker	wukcer	wufper	mifpan	OBCERT	obcert	ocbert	ondert	andimp
GONRAY	gonray	gornay	gophay	laphit	GOCSON	gocson	goscon	golron	halrab
HORTON	horton	hotron	hoklon	jaklaf	OBISAL	obisal	osibal	ozigal	ezugem
ROUSHT	rousht	rouhst	roudmt	baidmn	PINTRE	pintre	pitnre	pisbre	fusbla
BEKROT	bekrot	berkot	bescot	jascip	BLYINS*	blyins	bylins	brpins	frpewz
FUBGRY	fubgry	fugbry	fuwjry	nawjlt	GABILY	gabily	galiby	gahity	dohutp
BLAFES	blafes	bfales	bjares	zjirov	IMRAYS	imrays	irmays	icvays	ucvont
BEDOLE	bedole	belode	benofe	muna fu	VANKED	vanked	vakned	vaphed	ziphom
SHROOB	shroob	srhoob	slnoob	flneeg	FIGGLE	figgle	figlge	figthe	wontha

*Items removed from analyses due to high error rates

Chapter 3

The Influence of Lexical Skills on Letter Position Processing

Abstract

Studies have shown that the magnitude of the masked transposed letter (TL) priming effect changes across development (e.g., Acha & Perea, 2008; Castles et al., 2007; Ziegler et al., 2014). These changes have been interpreted as being driven by the development of lexical skills. However, an alternative interpretation is that changes in TL priming are caused by a general maturation of the visual system, independently of lexical development. Determining whether changes in TL priming are driven by increasing lexical skills or maturation (or both) is difficult, considering the two are inherently entwined in children learning to read. One way to disentangle the two is to investigate whether lexical skills influence TL priming in University students, as the relationship between lexical skill and age is likely to be far weaker in skilled adult readers than in primary school children. Following this logic, the present study was designed to test whether individual differences in lexical skills, defined by participants' reading, spelling and vocabulary performance, influence TL priming in 80 undergraduate University students. In contrast to previous studies with skilled readers, the TL priming effect was measured both as a facilitatory effect relative to an all-letters-different (ALD) prime (listen - LISTEN vs rodgup - LISTEN), and as a cost effect relative to an identity prime (listen - LISTEN vs listen - LISTEN). We found that words preceded by a TL prime were responded to significantly faster than words preceded by an ALD prime, and significantly slower than words preceded by an ID prime. However, the magnitude of these priming effects did not vary as a function of lexical skill. The results are discussed in relation to previous findings as well as current theories of letter position processing and reading development.

The Influence of Lexical Skills on Letter Position Processing

Introduction

Masked priming studies showing that adults are faster to respond to targets preceded by a transposed-letter (TL) prime (e.g., listen - LISTEN) relative to a substitution control (e.g., lidfen - LISTEN) suggest that letter position coding in skilled readers is somewhat flexible (e.g., Kinoshita, Castles, & Davis, 2009; Lupker & Davis, 2009; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2003, Perea & Lupker, 2004). Several studies have used the masked priming paradigm to investigate whether the degree of flexibility in letter position coding changes across development, with larger facilitatory TL priming effects indexing greater flexibility or tolerance within the visual word recognition system to manipulations of letter position. Using this approach, the developmental findings have been mixed: some studies have found a small decrease in the TL priming effect across development (Acha & Perea, 2008; Castles, Davis, Cavalot & Forster, 2007) suggesting that letter position is coded *more* precisely (or less flexibly) in older readers, while others have found an increase in the effect (Ziegler, Bertrand, Lété, & Grainger, 2014; Lété & Fayol, 2013), suggesting that letter position is coded *less* precisely in older readers.

Kezilas, McKague, Kohnen, Badcock, and Castles (submitted; see Chapter 2 of this thesis) recently argued that the baseline primes used to measure the TL priming effect might be contributing to the confusion within the literature. The two baselines typically used to measure the TL priming effect are the double-substituted-letter (2SL) prime (e.g., lidfen - LISTEN), formed by substituting two letters in the target (e.g., Acha & Perea, 2008; Ziegler et al., 2014), and the all-letters-different (ALD) prime (e.g., rodful - LISTEN), formed by substituting all letters in the target (e.g., Castles et al., 2007; Lété & Fayol, 2013). Since the 2SL and ALD prime are formed by manipulating letter identity, Kezilas et al. (submitted; Chapter 2) argued that the TL priming effect measured relative to

these baselines conflates letter position with letter identity effects, making it difficult to determine whether changes in priming across development are driven by changes in sensitivity to letter position manipulations, or in sensitivity to letter identity manipulations.

Kezilas et al. (submitted; Chapter 2) proposed that disambiguating letter position from letter identity effects requires considering the influence of the TL prime on target processing as a cost relative to the influence of an identity (ID) prime (e.g., listen - LISTEN), with a larger cost indicating that the system is less tolerant or flexible with regard to the letter position manipulation within the TL prime (see also Kinoshita et al., 2009). The advantage of this comparison is that both the TL and ID primes share all letter identities with the target, and hence differ only in letter position. Following this approach, Kezilas et al. (submitted; Chapter 2) found that the TL priming cost relative to the ID baseline prime increased across development (grades 2-6 and adults tested). The authors interpreted this finding within the context of the lexical tuning hypothesis (Castles et al., 2007; Forster, Davis, Schoknecht, & Carter, 1987; Forster & Taft, 1994). They argued that during the early stages of reading development, the visual word recognition system is relatively tolerant to orthographic manipulations, such that the cost of transposing two letters (TL prime) in the target is minimal. As a child's sight word vocabulary develops, the system must tighten its input criterion in order to minimize competition between visually similar words (e.g., *pat*, *tap*, *apt*). This tightening up or 'tuning' of the system means that letter position manipulations come at a larger cost as reading develops.

However, an alternative interpretation of Kezilas et al.'s finding (submitted; Chapter 2) is that an increase in the TL cost across development is brought about by a general maturation of the visual system. Some models of visual word recognition posit that letter position effects are caused by generic noise or uncertainty that is imposed upon the visual system (Overlap model: Gomez, Ratcliff, & Perea, 2008; Bayesian Reader: Norris, 2006; Norris, Kinoshita, & Casteren, 2010). These models suggest that position effects are

not unique to reading, and that TL priming is a reflection of the perceptual ambiguities inherent to visual object recognition. Following this logic, the increased cost of the TL prime across development reported by Kezilas et al. (submitted; Chapter 2) could be the result of a reduction in noise or uncertainty in the coding of letter positions within words – independently of lexical development.

Determining whether a change in the magnitude of the TL priming effect is driven by lexical development or perceptual maturation (or both) is difficult, considering the two are inherently entwined in children learning to read. One way to disentangle the two is to investigate whether lexical skills influence the magnitude of TL priming in University students. Whilst University students vary in both age and lexical skill, any relationship between the two variables is likely to be much weaker (if present at all) than in primary school children who are still undergoing reading instruction. Therefore, if a relationship were found between lexical skills and the magnitude of masked priming effects in adult readers, the basis of change in developing readers might be more confidently attributed to the development of lexical skills.

Andrews and Lo (2012) recently reported a study investigating TL priming effects in a sample of University students and found that the size of the TL priming effect, measured against an ALD baseline, was mediated by lexical skill. Lexical skill was estimated by a principal component based on reading, spelling and vocabulary performance, and was argued to provide an index of the precision of a reader's orthographic representations, in line with Perfetti's lexical quality hypothesis (Perfetti, 1992; Perfetti, 2007). According to this account, precise orthographic representations encode the identity and position of letters in words known to the reader, and support automated word recognition. Andrews and Lo (2012) found that the adults in the sample with the poorest lexical skills displayed a large TL priming effect (approximately 25ms), and the priming effect gradually diminished with increasing lexical skill (see Adelman,

Johnson, McCormick, McKague, Kinoshita, Bowers et al., 2014 for a similar result using vocabulary to index lexical skill). Based on this finding, Andrews and Lo (2012) concluded that readers with relatively weak lexical skills – and hence with less precise orthographic representations – are more likely to show facilitatory priming effects, as the orthographic representation for the target word is preactivated by the TL prime, despite the prime not being an exact match to the target. With increasing lexical skill, the TL priming effect diminishes, indicating that target processing is no longer facilitated by a prime that differs from it via the transposition of two letters (Andrews & Lo, 2012).

Whilst this finding reported by Andrews and Lo (2012) is certainly consistent with the hypothesis that TL priming is modulated by lexical skills, it is somewhat difficult to interpret given that the authors measured TL priming against an ALD baseline. As argued by Kezilas et al. (submitted; Chapter 2), the TL prime and ALD prime differ in their relationship with the target in two critical ways: (1) the TL prime transposes two letters within the target whereas the ALD prime does not, and (2) the TL prime shares all letter identities with the target whereas the ALD shares none. It is therefore difficult to ascertain whether the TL priming effect for those with relatively weak lexical skills reported by Andrews and Lo (2012) is driven by the letter position manipulation within the TL prime, or by the fact that the TL prime shares all letter identities with the target whereas the ALD prime does not. The interpretation of Andrews and Lo's finding (2012) is further complicated by the influence of lexical skill on single-substitution-letter (1SL) priming (e.g., *wiup* - *WISP* vs *truv* - *WISP*) reported within the same study, with the same targets. Whilst the magnitude of the TL priming effect was found to decrease with lexical skill, the 1SL priming effect increased (relative to the ALD prime), suggesting a differential influence of lexical skills on a reader's sensitivity to letter position manipulations and letter identity manipulations.

The aim of the present study was to clarify whether lexical skills influence TL

priming in skilled adult readers, with the hope that the findings could be used to inform theories of letter position development. We extended the methodology described in Kezilas et al. (submitted; Chapter 2) to a sample of University students and indexed lexical skill using a reading, spelling and vocabulary measure. We expected to replicate Andrews and Lo's finding (2012) that TL priming relative to the ALD prime decreases as lexical skills increase. The novel feature of the present study was the inclusion of the ID prime. Since the TL prime and the ID prime both share all letter identities with the target, comparing the TL prime to the ID prime removes the potential conflation of letter position and letter identity effects inherent to the TL-ALD comparison. Following the hypothesis that lexical skills influence letter position processing, we expected the cost of the TL prime relative to the ID prime to increase as lexical skills increase – a finding that would be consistent with the proposal that letter position is processed more precisely in readers with superior lexical skills.

Method

Participants

Eighty undergraduate students (71 females) from Macquarie University took part in the experiment in exchange for course credit. Data from forty of the participants were also included in the analyses reported by Kezilas et al. (submitted; Chapter 2). All participants had normal or corrected-to-normal vision and were native speakers of English.

Measures of Lexical Skill

Participants were tested on three measures of lexical skill: sight word reading efficiency, spelling-to-dictation, and vocabulary. Their scores on each test are reported in Table 1.

Reading was measured using the sight word efficiency subtest of the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999). The test measured the number of words participants could name in 45 seconds. Four lists of 26 words were

presented, and participants were instructed to read down each list before proceeding to the next. The words increased in difficulty as the test went on. Participants were told to stop reading after 45 seconds, and the number of words read correctly was tallied.

Vocabulary was tested using Shipley-2 (Shipley, Gruber, Martin, & Klein, 2009). The test consisted of 40 items. For each item, participants were presented with a written word in capital letters (e.g., *TALK*), and asked to circle one word out of four alternatives that had the same meaning as the word in capitals (e.g., *draw, eat, speak, sleep*). The items increased in difficulty as the test progressed. Following standardized administration, participants were given up to 10 minutes to complete the 40 items.

The spelling-to-dictation test comprised 50 words (8-10 letters long) selected from Burt and Tate (2002). Each word was first verbally presented, then included within a carrier sentence to clarify its meaning, and then repeated. Participants wrote their spelling responses by hand in a booklet provided.

Table 1. Mean, standard deviation (SD), and minimum and maximum scores on the sight word reading, vocabulary and spelling test.

		Mean	SD	Min - Max
Age (years)		23.13	8.53	17.84 - 40.50
Sight word reading (TOWRE)	Raw	88.81	8.83	63 - 104
	Standard Score*	91.53	9.35	72 - >113
Vocabulary (Shipley-2)	Raw	30.30	4.03	15 - 36
	Standard Score	108	9.17	72 - 121
Spelling		25.80	10.40	3 - 49

*All standard scores are based on normative data from ages 17-25.

Experimental Design and Stimuli

The targets and primes (TL, ALD, and ID) used in the present study were the same as those reported in Kezilas et al. (submitted; Chapter 2). Targets were 72 words and 72 nonwords that were 5 and 6 letters long ($M = 5.64$, $SD = 0.48$). Target words had a mean of 2.53 ($SD = 2.86$) neighbours using Coltheart's N (Coltheart, Davelaar, Jonasson, & Besner, 1977), and a mean CELEX written word frequency of 259.81 per million ($SD = 351.77$). Frequency and neighbourhood estimates were obtained using N-Watch (Davis, 2005). Each target word was paired with a transposed-letter (TL) prime (e.g., nubmer - NUMBER), an all-letters-different (ALD) prime (e.g., boj dip - NUMBER), and an identity (ID) prime (e.g., number - NUMBER). The TL primes were formed by transposing two internal consonants within the word. Target nonwords were matched to words for CV structure, and were paired with a TL prime, ALD prime and an ID prime. For further details about the stimuli, see Kezilas et al. (submitted; Chapter 2).

Procedure

Participants first completed the lexical decision task, followed by the reading, spelling and vocabulary tests. The lexical decision task was administered using DMDX software (Forster & Forster, 2003). An external button box was used to record response times and error rates. Each trial began with a string of hashmarks presented for 500ms, followed by the prime in lowercase for 50ms. The prime was then backward masked by the target for up to 10 seconds, or until a response was made. Participants were asked to respond as accurately and as quickly as they could. They completed 6 blocks, with two buffer items at the beginning of each block. Buffer items were excluded from the analysis. Separate experimental lists were created such that participants saw each target only once in a single condition. Items were randomised for each individual.

Data Treatment

A measure of lexical skill was computed for each participant by first converting

their raw scores on each test to Z-scores, and then calculating participants' mean Z-score for the three tests. Correlations amongst the three tests were moderate (reading and spelling $r = .37, p < .01$; reading and vocabulary $r = .28, p < .05$; spelling and vocabulary $r = .34, p < .01$).

Trials on the lexical decision task with response times more than 2000ms were excluded from the analysis, comprising <1% of the data in total. One participant who made excessive errors on the task was removed from the analysis. Errors were excluded from the RT analyses. RTs were inverse transformed ($1000/RT$) prior to the analysis to normalise the data and reduce the impact of outliers (Ratcliff, 1993). The untransformed RT data are reported in Table 2. Accuracy data and nonword data were not analysed as we had no clear predictions in regards to the effects. Nevertheless the accuracy data and nonword data are included in Table 2 for completeness. Observation of the RT data relative to the accuracy data revealed no evidence for any speed-accuracy trade off.

Results

Linear mixed effects modelling was used to analyse the inverse RT data, and p values were obtained using lmerTest package (Kuznetsova, Brockhoff & Christensen, 2015). Two separate analyses were conducted: TL vs ALD and ID vs TL. Three models for each analysis were compared: (1) a model including the main effect of prime type, (2) a model including the main effect of prime type and the main effect of lexical skill, and (3) a model including the main effects of prime type and lexical skill, as well as the interaction between these two variables. Subjects and items were included in the models as random effects. The models were compared pair-wise in order of complexity. Model (1) was compared to an intercept-only model. The best fitting model was that which provided the lowest AIC value of the three models tested, whilst also providing a significantly better fit to the data than the simpler model it was compared to.

For both analyses (TL vs ALD, ID vs TL), the best fitting model was Model 2, which included the main effect of prime type, and the main effect of lexical skill (TL vs ALD model: $\chi^2(1) = 4.48, p < .05$; ID vs TL model: $\chi^2(1) = 4.35, p < .05$). While Model 3 (interaction between prime type and lexical skill) did not significantly improve the fit to the data, both $ps > .13^1$, the estimates for this model are presented in Figure 1 so as to not obscure potential non-significant trends in the data.

For both sets of analyses, response times were faster for those with superior lexical skills (TL vs ALD model: $t = 2.15, p < .05$; ID vs TL model: $t = 2.12, p < .05$). Words preceded by a TL prime were responded to significantly faster than words preceded by an ALD prime, $t = 7.76, p < .001$, and response times to words preceded by a TL prime were significantly slower than response times to words preceded by an ID prime, $t = 7.31, p < .001$.

¹ We also created two extreme groups comprising the top and bottom 25 scores in the sample, with the idea that perhaps this would provide a more sensitive index of lexical skill. The interaction between priming and the extreme groups did not significantly improve the fit of the model (both $ps > .18$). Furthermore, since the correlations between the lexical skill measures were only moderate, we ran both sets of analyses (TL-ALD and ID-TL) including each test separately. None of the interactions between priming and the test scores (Z transformed) significantly improved the fit to the data (all $ps > .07$). Two extreme groups for each test were also created (top and bottom 25 scores in the sample). None of the interactions between priming and the extreme reading, spelling or vocabulary groups significantly improved the fit to the data (all $ps > .24$).

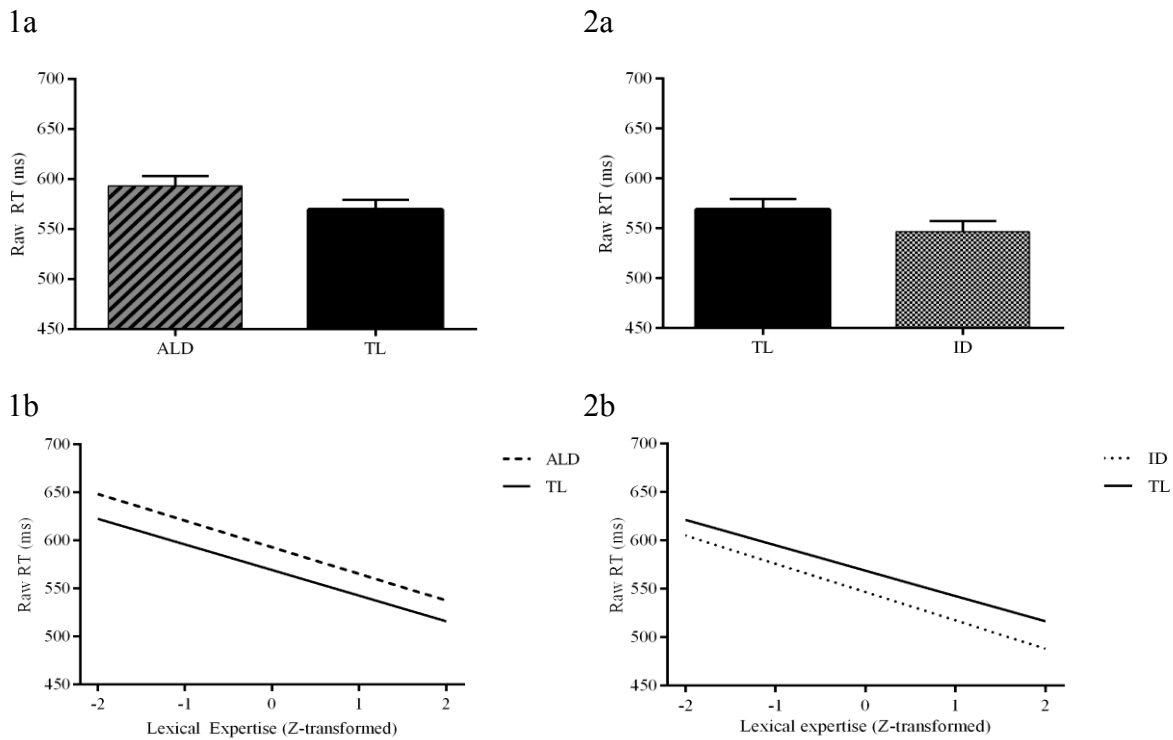


Figure 1. Untransformed RT estimates for the model including the TL-ALD by lexical skill interaction (1), and the model including the ID-TL by lexical skill interaction (2). Panel 1a and 2a show the estimated mean RT and standard error, and Panel 1b and 2b show the estimated RT as a function of lexical skill. Mean RTs rather than inverse transformed RTs are presented for ease of interpretation.

Table 2. Untransformed response times and accuracy rates for words and nonwords in each prime condition based on the raw data. Numbers in parentheses denote the standard deviation of the mean.

		RT (ms)	Accuracy (%)
Words	ID	546.15 (92.87)	98.73 (2.35)
	TL	568.07 (84.82)	96.48 (5.28)
	ALD	592.26 (80.24)	96.13 (5.29)
Nonwords	ID	704.44 (164.34)	95.49 (6.03)
	TL	689.01 (154.60)	93.00 (9.56)
	ALD	713.59 (156.76)	94.93 (9.16)

The finding that lexical skills did not interact with TL priming was somewhat surprising given that Andrews and Lo (2012) had previously reported a relationship between lexical skills and the magnitude of TL priming in skilled adult readers. Our target words differed from Andrews & Lo's (2012) in two key ways: they had significantly fewer neighbours, where a neighbour is defined as a word that differs from the target by a single letter (present study $M = 2.53$, $SD = 2.86$; Andrew & Lo $M = 4.64$, $SD = 3.71$, $p < .01$), and they were significantly higher in written frequency (present study $M = 259.81$, $SD = 351.77$; Andrews & Lo $M = 7.61$, $SD = 10.09$, $p < .001$). Both neighbourhood density and frequency have been found to influence target response times in psycholinguistic tasks. For example, target words from dense neighbourhoods (high-N words) typically produce smaller facilitatory priming effects than targets from sparse neighbourhoods (low-N words; Forster et al., 1987), and there is evidence that target word N interacts with lexical skills to influence the magnitude of form priming effects (Andrews & Hersch, 2010, Experiment 1; Castles et al., 2007). Furthermore, a wealth of research has shown that high frequency words are typically responded to faster than low frequency words (see Monsell, 1991 for a

review), and there is also evidence to suggest that this frequency effect might be attenuated in readers with superior lexical skills (Sears, Siakaluk, Chow, & Buchanan, 2008; Ashby, Rayner, & Clifton, 2005). Following these findings, it is possible that our failure to replicate Andrews & Lo's results (2012) was due to differences in item-level variables between the two studies, such as target N and frequency.

To this end, we conducted a series of follow-up analyses to investigate whether including target N and frequency might reveal a more nuanced relationship between lexical skills and priming modified by these item-level variables. Four separate analyses were conducted to investigate (1) the influence of N on the TL vs ALD and lexical skill analysis, (2) the influence of N on the ID vs TL and lexical skill analysis, (3) the influence of frequency on the TL vs ALD and lexical skill analysis, and (4) the influence of frequency on the ID vs TL analysis.

Four models were compared for each of the four analyses: (1) a model including the interaction between lexical skill and prime type, and the main effect of the item-level variable (i.e., N *or* frequency), (2) a model including the interaction between prime type and lexical skill, and the interaction between the lexical skill and the item-level variable, (3) a model including the interaction between prime type and lexical skill, the interaction between the prime type and the item-level variable, and the interaction between lexical skill and the item-level variable, and (4) a model including the three way interaction between prime type, lexical skill, and the item-level variable. The models included subjects and items as random effects. Models were compared pairwise in order of complexity. Model (1) was compared to a simpler model including the interaction between prime type and lexical skill only.

None of the models including target word N provided a significantly better fit to the data than the model including the interaction between prime and lexical skill (TL-ALD: all $ps > .26$; ID-TL: all $ps > .18$), indicating that target N had no influence on response

times in the lexical decision task.

When considering the effect of target frequency, the best fitting model for the TL vs ALD analysis was Model 1 including the main effect of frequency, $\chi^2(1) = 4.92$, $p < .05$, indicating that participants were faster to respond to higher frequency target words than to lower frequency target words. For the ID-TL analysis, the best fitting model was Model 2 including the interaction between lexical skill and frequency, $\chi^2(1) = 8.10$, $p < .01$. The interaction reflected that faster response times for participants with high lexical skill relative to those with low lexical skills was larger for low frequency targets than for high frequency targets. This interaction is presented in Figure 2, where a median split on the lexical skill scores has been conducted for ease of interpretation. These results reflect an attenuation of the frequency effect in participants with higher levels of lexical skill, but there was no evidence that the presence of this frequency attenuation effect in the sample was obscuring an underlying relationship between lexical skill and priming.

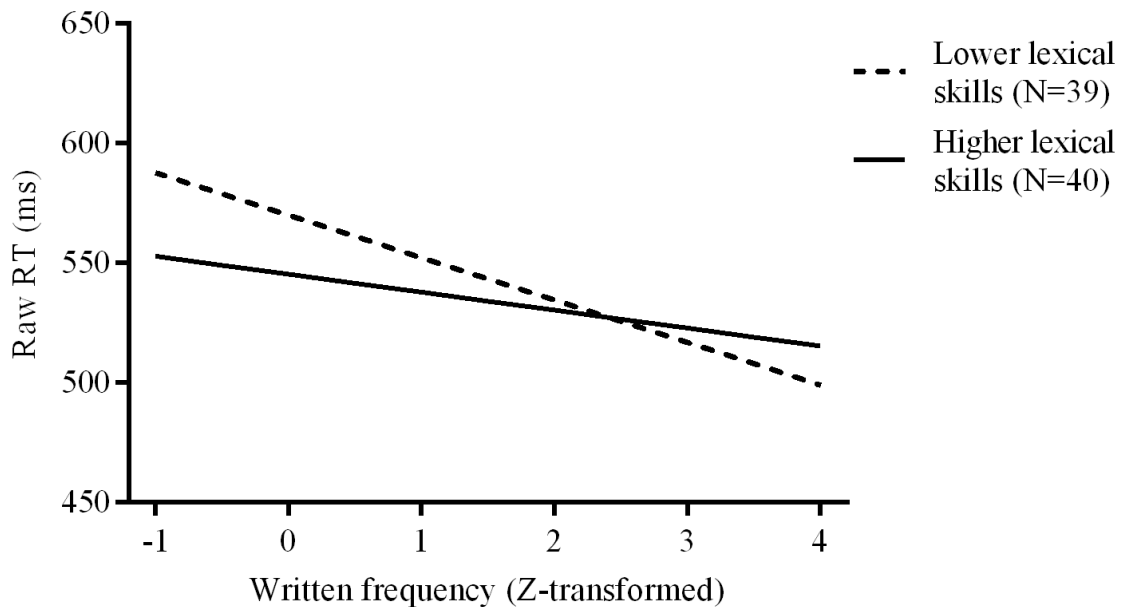


Figure 2. Untransformed RT estimates from the best fitting model (Model 2) for the interaction between lexical skill (presented as a median split), and frequency.

Discussion

The aim of the present study was to investigate whether lexical skills influence the magnitude of the TL priming effect in University students, with the aim of using the results to inform theories of letter position development. The results were clear-cut. Whilst responses to words preceded by a TL prime were significantly faster than responses to words preceded by an ALD prime, this effect was not mediated by individual differences in lexical skill. Investigating the influence of the TL prime as a cost effect relative to the ID prime – a comparison that has been argued to offer a purer index of letter position processing (Kezilas et al., submitted; Chapter 2; Kinoshita et al., 2009) – provided complementary results; responses to targets preceded by a TL prime were significantly slower than responses to targets preceded by an ID prime, but again lexical skills did not influence the magnitude of the cost effect.

The significant TL priming effect relative to the ALD prime found in the present study is consistent with previous research showing the skilled visual word recognition system to be somewhat tolerant to the manipulation of letter position within words (e.g., Kinoshita et al., 2009; Lupker & Davis, 2009; Lupker et al., 2008; Perea & Lupker, 2003; Perea & Lupker, 2004). Despite not being an exact match to the target, the TL prime preactivates the orthographic representation for the target word, providing it with a head start in the lexical decision process. However, the finding that the TL prime also slowed responses relative to a prime that is an exact match to the target (the ID prime), suggests that letter position manipulations do come at a cost. By comparing the TL prime to a prime that is an exact match to the target (the ID prime) and a prime that is an exact *mismatch* to the target (the ALD prime), we were therefore able to demonstrate that a fine balance between precision and flexibility characterises letter position coding in skilled adult readers.

The finding that TL priming (measured both as an advantage and a cost) did not

interact with lexical skill in the present study was somewhat surprising in light of Andrews and Lo's (2012) results. Relative to an ALD prime, Andrews and Lo (2012) found facilitatory TL priming for readers with relatively weak lexical skills, which gradually diminished with increasing lexical skill. In a follow-up analysis, we investigated whether the discrepancy between the present findings and those reported by Andrews and Lo (2012) was due to differences between the two studies in the characteristics of the target words used. Specifically, our target words had significantly fewer neighbours than those used in Andrews and Lo's study (2012), and were significantly higher in written frequency – an observation that spurred an investigation into the potential modulating role of target N and frequency on the relationship between lexical skills and TL priming. Again, the results from the follow-up analyses were clear: the relationship between lexical skills and priming was not influenced by target word N or frequency, despite the presence of a frequency attenuation effect for those with higher lexical skills.

An alternative explanation for our inability to replicate Andrews and Lo's finding (2012) is that our measure of lexical skill was not sensitive enough to capture individual differences in TL priming. Andrews & Lo (2012) indexed lexical skill in a similar way to the present study but, in their study, more than one test was used to measure reading and spelling performance – reading performance was measured using participants' text reading fluency and their reading comprehension, and spelling was measured using both spelling-to-dictation and spelling recognition performance. Furthermore it could be that there was more variability in lexical skills within Andrews and Lo's (2012) sample – as can be seen in Table 1, there was limited variability amongst participants' reading and vocabulary performance in the present study. However, it should be noted that our measure of lexical skill was sensitive enough to discriminate between skilled readers in the size of the frequency effect, and was therefore potentially sensitive enough to discriminate between skilled readers in the size of the priming effect - notwithstanding that the size of the TL

priming effect is smaller than the frequency effect.

Our inability to replicate Andrews and Lo (2012) may also be due to differences between the two samples tested. The overall facilitatory priming effect in the present study was larger than the effect reported by Andrews and Lo (24ms vs 7ms respectively). Following the idea that those with superior lexical skills show smaller form priming effects, it may be that Andrews and Lo's sample consisted of more individuals with exceptional lexical skills than in the present study. Whether or not this is the case is difficult to determine, however, as participants' scores on the lexical skill measures were not reported in Andrews and Lo's study (2012).

In conclusion, the findings from the present study provided no evidence to support the hypothesis that individual differences in lexical skills influence letter position processing in skilled adult readers. Taken at face value, our findings suggest that previous reports of changes in letter position processing across development are not driven by the development of lexical skills, and may therefore be driven by other factors, such as a general maturation of the visual system. However, it is difficult to make strong conclusions in light of the discrepancy between our findings and those reported by Andrews and Lo (2012), and the possibility that our ability to capture individual differences in priming was hindered by the limited sensitivity of our measures, and the limited variability amongst participants in lexical skill. A replication of the findings from the present study, including more sensitive measures of lexical skill and a more variable sample, is therefore required before developing lexical skills can be confidently ruled out as a factor influencing changes in letter position processing across development.

References

- Acha, J., & Perea, M. (2008). The effects of length and transposed-letter similarity in lexical decision: Evidence with beginning, intermediate, and adult readers. *British Journal of Psychology*, 99, 245-264. doi: 10.1348/000712607X224478
- Ashby, J., Rayner, K., & Clifton, C. (2005). Eye movements of highly skilled and average readers: Differential effects of frequency and predictability. *The Quarterly Journal of Experimental Psychology Section A*, 58(6), 1065-1086. doi: 10.1080/02724980443000476
- Burt, J. S., & Tate, H. (2002). Does a reading lexicon provide orthographic representations for spelling? *Journal of Memory and Language*, 46(30), 518-543, doi: 10.1006/jmla.2001.2818
- Castles, A., Davis, C., Cavalot, P., & Forster, K. (2007). Tracking the acquisition of orthographic skills in developing readers: Masked priming effects. *Journal of Experimental Child Psychology*, 97, 165-182. doi:10.1016/j.jecp.2007.01.006
- Coltheart, M., Davelaar, E., Jonasson, J. T., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Eds.), *Attention and Performance VI*. (Hillsdale, NJ: Erlbaum.
- Davis, C. J. (2005). N-Watch: A program for deriving neighbourhood size and other psycholinguistics statistics. *Behaviour Research Methods*, 37(1), 65-70. doi: 10.3758/BF03206399
- Forster, K. I., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology*, 39, 211-251.
- Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers*, 35(1), 116-124.

- Forster, K. I., & Taft, M. (1994). Bodies, antibodies, and neighbourhood density effects in masked form priming. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 20(4), 844-863. doi: 10.1037/0278-7393.20.4.844
- Gomez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: a model of letter position coding. *Psychological Review*, 115(3), 577.
- Kezilas, Y., McKague, M., Kohnen, S., Badcock, N. A., & Castles, A. (submitted, 2015). Disentangling the developmental trajectories of letter position and letter identity coding using masked priming. *Journal of Experimental Psychology: Learning, Memory and Cognition*.
- Kinoshita, S., Castles, A., & Davis, C. (2009). The role of neighbourhood density in transposed-letter priming. *Language and Cognitive Processes*, 24(4), 506-526. doi: 10.1080/01690960802289213
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2015). *lmerTest: Tests in Linear Mixed Effects Models*. R package version 2.0-29. <http://CRAN.R-project.org/package=lmerTest>
- Lété, B., & Fayol, M. (2013). Substituted-letter and transposed-letter effects in a masked priming paradigm with French developing readers and dyslexics. *Journal of Experimental Child Psychology*, 114(1), 47-62. doi: 10.1016/j.jecp.2012.09.001
- Lupker, S. J., & Davis, C. J. (2009). Sandwich priming: a method for overcoming the limitations of masked priming by reducing lexical competitor effects. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 35(3), 618-639. doi: 10.1037/a0015278
- Lupker, S. J., Perea, M., & Davis, C. (2008). Transposed-letter effects: Consonants, vowels and letter frequency. *Language and Cognitive Processes*, 23(1), 93-116. doi: 10.1080/01690960701579714

- Monsell, S. (1991). The nature and locus of word frequency effects in reading. In D. Besner & G. W. Humphreys (Eds.), *Basic processes in reading: Visual word recognition*. Hillsdale, NJ: Erlbaum.
- Norris, D. (2006). The Bayesian Reader: Explaining word recognition as an optimal Bayesian decision process. *Psychological Review*, 113(2), 327-357. doi: <http://dx.doi.org/10.1037/0033-295X.113.2.327>
- Norris, D., Kinoshita, S., & Casteren, M. (2010). A stimulus sampling theory of letter identity and order. *Journal of Memory and Language*, 62(3), 254-271. doi: 10.1016/j.jml.2009.11.002
- Perea, M., & Lupker, S. J. (2003). Transposed-letter confusability effects in masked form priming. In S. Kinoshita and S. J. Lupker (Eds.), *Masked priming: State of the art*. Hove, UK: Psychology Press.
- 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. doi:10.1016/j.jml.2004.05.005
- Perfetti, C. A. (1992). The representation problem in reading acquisition. In P. B. Gough, L.C. Ehri, & R. Treiman (Eds.), *Reading acquisition*. Hillsdale, NJ: Erlbaum.
- Perfetti, C. A. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading*, 11(4), 357-383. doi:10.1080/10888430701530730
- Ratcliff, R. (1993). Methods for dealing with reaction time outliers. *Psychological Bulletin*, 114(3), 510-532. doi:10.1037/0033-2909.114.3.510
- Sears, C. R., Siakaluk, P. D., Chow, V. C., & Buchanan, L. (2008). Is there an effect of print exposure on the word frequency effect and the neighbourhood size effect? *Journal of Psycholinguistic Research*, 37(4), 269–291.
- Shipley, W. C., Gruber, C. P., Martin, T. A., & Klein, A. M. (2009). Shipley-2. Los Angeles, CA: Western Psychological Services.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). Test of word reading efficiency.

Austin, TX: ProEd.

Ziegler, J. C., Bertrand, D., Lété, B., & Grainger, J. (2014). Orthographic and phonological contributions to reading development: Tracking developmental trajectories using masked priming. *Developmental Psychology*, 50(4), 1026-1036. doi: 10.1037/a0035187

Chapter 4

Word and Pseudoword Superiority Effects on Letter Position Processing in Developing and Skilled Readers

Abstract

Studies have shown that letter position processing changes as reading develops. Whether or not reported changes in letter position processing across development are driven by changes occurring within the lexicon is currently unclear. In this study, we administered a novel variant of the well-established Reicher-Wheeler task to both children in aged 7-12 years (Experiment 1) and adults (Experiment 2) in order to clarify the role of the developing lexicon in letter position processing. The task required participants to report the identity of a letter at a specified position within three orthographic contexts: anagram words (e.g. *form* – which has the anagram partner, *from*), pseudowords (e.g., *pilf* – *plif*) and illegal nonwords (e.g. *ftkl* – *ftkl*). The influence of a reader's whole-word orthographic representations was investigated by comparing the performance of words to pseudowords (*word superiority effect*), and the influence of their knowledge of orthotactic constraints on letter position processing was investigated by comparing performance for pseudowords to illegal nonwords (*pseudoword superiority effect*). Whilst the pseudoword superiority effect was found to increase with developing orthographic knowledge in primary school children, the word superiority effect emerged only in skilled adult readers. The findings are discussed in regards to current models and theories of visual word recognition and reading development.

Word and Pseudoword Superiority Effects on Letter Position Processing in Developing and Skilled Readers

Introduction

There has been much recent interest in how the mind processes the position of letters within words (e.g., Andrews & Lo, 2012; Kinoshita, Castles, & Davis, 2009; Frost, 2012; Kohnen & Castles, 2013; Lupker & Davis, 2009; Lupker, Perea, & Davis, 2008; Paterson, Read, McGowan, & Jordan, 2014; Perea & Lupker, 2003; Perea & Lupker, 2004; Rayner, White, Johnson, & Liversedge, 2006). Recognizing and comprehending a written word requires the reader not only to identify each of its component letters but also to determine the order of those letters, such that *pat* can be differentiated from *apt* and *tap*. Reports of individuals with *letter position dyslexia*, who make excessive letter position errors such as reading *form* as “from” or defining *diary* as “something that comes from a cow”, highlight the importance of letter position processing for successful reading (Friedmann & Rahamim, 2007; Friedmann, Dotan, & Rahamim, 2010; Friedmann, Gvion, & Nisim, 2015; Friedmann & Haddad-Hanna, 2012; Kohnen, Nickels, Castles, Friedmann, & McArthur, 2012; Kezilas, Kohnen, McKague, & Castles, 2014; see Chapter 5 of this thesis). Therefore, determining how the letter position processing system functions, and what the sources of individual variability are, is critical for understanding typical as well as impaired reading.

A key unanswered question is whether the letter position processing system changes as reading develops and, if so, in what way. The evidence to date is mixed. For example, the results of some studies indicate that adults process letter position more precisely than children (e.g., Acha & Perea, 2008; Perea & Estevez, 2008; Grainger, Lété, Bertand, Dufau, & Ziegler, 2012), while other studies report no difference (Paterson, Read, McGowan, & Jordan, 2014). Studies that have looked at developmental changes across the critical years of reading acquisition (approximately ages 6-12) have also produced a range

of findings: Some studies have reported no significant changes in letter position processing across this age range (Perea & Estevez, 2008); others have reported a trend towards older children processing letter position more precisely than younger children (Acha & Perea, 2008; Castles, Davis, Cavalot, & Forster, 2007), while still others have reported that letter position information is processed less precisely (or more ‘coarsely’) in older children than in younger children (Ziegler, Bertrand, Lété, & Grainger, 2014).

These mixed findings may reflect the fact that there is more than one possible source of developmental change in the ability to resolve letter position during visual word recognition. In models of reading, letter position is typically represented at the initial encoding stage of visual word recognition, where a letter’s identity and position are analysed prior to lexical access (see Grainger & van Heuven, 2003 for a review of these models). For this reason, studies that have found a change in letter position effects across reading development have suggested this is most likely due to changes in the way letters are encoded (Acha & Perea, 2008; Grainger et al., 2012; Grainger & Ziegler, 2011; Ziegler et al., 2014). For example, based on Perea and Estevez’s (2008) finding that children make more errors than adults when reading aloud ‘migratable’ nonwords (e.g., *cholocate* → “chocolate”) relative to control nonwords (e.g., *choronate* → “chocolate”), it has been proposed that the letter encoding system may become more precise (or less noisy) as the visual system matures (Gomez, Ratcliff, & Perea, 2008; Perea & Estevez, 2008).

A second possibility that has yet to be systematically explored is that changes in letter position effects across development are driven by changes occurring at a later stage in the reading system than the initial encoding of letter position. It has been well-established, at least for letter identification, that performance on basic detection tasks is heavily influenced by factors thought to reflect processes subsequent to letter encoding, such as orthographic context. Indeed, letters tend to be identified more accurately when they are presented within the context of word than within a pseudoword (*word superiority*

effect or *WSE*), and when presented within the context of a pseudoword than within an illegal nonword (*pseudoword superiority* effect or *PSE*; e.g., Chase & Tallal, 1990; Coch & Mitra, 2010; Grainger & Jacobs, 1994; Johnston & McClelland, 1974; Juola, Schadler, Chabot, & McCaughey, 1978; Reilhac, Jucla, Iannuzzi, Valdois, & Demonet, 2012). These effects reflect the influence of orthographic knowledge on letter identification, where orthographic knowledge is defined as a reader's set of stored whole-word orthographic representations (i.e., memory traces for written words), as well as their awareness of orthotactic constraints (e.g., knowing that *mb* does not form a legal onset in English). Despite the high correlation between these two contributions to orthographic knowledge, the WSE and PSE offer a means to study them independently of one another: the WSE is used to investigate the influence that a reader's stored whole-word orthographic representations have on letter identification (over and above the influence of orthotactic constraints), while the PSE is used to investigate the influence of just sub-word level orthotactic constraints.

There is also evidence that the influence of orthographic knowledge on letter identification increases across reading development. For example, skilled adult readers tend to show a larger word (Grainger et al., 2003; Lété & Ducrot, 2008) and pseudoword (Chase & Tallal, 1990) superiority effect than children, older children have been found to show a larger pseudoword superiority effect than younger children (Juola et al., 1978), and children with dyslexia have been found to show no word or pseudoword superiority effects at all (Chase & Tallal, 1990). If the ability to determine letter *position* is similarly influenced by orthographic knowledge, then reported changes in letter position effects across reading development might not reflect changes in the encoding of letter position per se. Rather, these apparent changes in letter position may be driven, at least in part, by changes in the influence of higher-level orthographic knowledge on letter processing.

The present study was designed to test this possibility. To do so, we developed a

novel adaptation of the classic Reicher-Wheeler task (Reicher, 1969; Wheeler, 1970). Since its development, the Reicher-Wheeler task has been the most popular tool to investigate the influence of higher-level orthographic knowledge on letter identification. In the standard version of the task, participants are asked to identify which of two letters was displayed at a cued position within a briefly presented string of letters. For example, the letter-string *slime* would be presented, the fourth position cued, and the participant asked to decide whether they saw *m* or *d*. Critically, when the target is a word, both letter options produce a word (e.g., substituting the fourth position in the word *slime* with the letter *d* produces the word *slide*), but only one is consistent with the target word, obviating a lexical guessing strategy. Letter identification for words is typically compared to pseudowords (to observe a word superiority effect) and letter identification for pseudowords is compared to illegal nonwords (to observe a pseudoword superiority effect).

To investigate the influence of orthographic knowledge on letter position processing, we modified the standard task in one key way: both the target letter and the foil letter are present within the input string. For example, the letter-string *slime* is presented, the fourth position cued, and the participant then asked to decide whether they saw *m* or *l* in that position. This differs from the standard letter identity version of the task in that the participant must have encoded the exact position of the letters in the input string in order to discriminate the two options. This simple modification provides a means to investigate the influence of orthographic context on the fine discrimination of letter positions within words.

In Experiment 1, we administered our novel letter position Reicher-Wheeler task, as well as the standard letter identification version of the task, to a group of 7-12 year old children. Based on previous research, we expected the WSE and PSE for the standard letter identification task to be negligible in children with limited orthographic knowledge. With

the development of orthographic knowledge, the WSE and PSE should begin to emerge, with the children in the sample with the most advanced orthographic knowledge displaying the largest WSE and PSE. If orthographic knowledge influences letter position and letter identity processing similarly, we should find a similar pattern of results for our novel letter position task. In Experiment 2 we administered the same task to a group of University undergraduate students to investigate whether orthographic knowledge plays a larger role in accurate letter processing for skilled adult readers than for developing readers.

Experiment 1

Method

Participants. Eighty-one children (41 males) between the ages of 7 and 12 ($M = 9$ years, 6 months; $SD = 1$ year, 3 months) from a suburban school in Sydney, Australia, took part in the experiment.

Measuring orthographic knowledge. The irregular words from the Castles and Coltheart Reading Test (CC2; Castles, Coltheart, Larsen, Jones, Saunders, & McArthur, 2009) were used to index orthographic knowledge in our sample of participants. Participants read aloud each word, one at a time, on separate flashcards. The CC2 also includes the administration of 40 regular words and 40 pronounceable nonwords, which are intermixed with the irregular words in the test. As we were solely interested in measuring orthographic knowledge, the regular words and nonwords were not analysed in this study.

Reicher-Wheeler task materials. Targets were 32 words, 32 pseudowords and 32 illegal nonwords that were 4 to 6 letters in length (see Appendix). Each word was selected to have an internal substitution neighbor and an internal migration neighbor (e.g., *slime* – *slide*, *smile*; *beard* – *bread*, *broad*). Substitution and migration neighbors were matched list-wise on CELEX written word frequency using N-Watch (substitution frequency $M = 27.22$, $SD = 41.05$, migration frequency $M = 25.53$, $SD = 45.35$; Davis, 2005).

Substitution and migration neighbors did not differ significantly on the combined number of substitution, deletion and addition neighbours (substitution $M = 8.69$, $SD = 3.94$; migration $M = 7.72$, $SD = 5.26$; $t < 1$). Each word's substitution neighbour and migration neighbour was used to create the foil letters in the letter identity and letter position conditions respectively. For example, if the target *slime* was presented and the fourth position cued, the letter *m* would be the correct alternative, the letter *d* would be the foil in the letter identity condition, and the letter *l* would be the foil in the letter position condition.

Pseudowords were also selected to have an internal substitution neighbour and an internal migration neighbor (e.g., *blire* – *blide*, *brile*; *kirlp* – *kirmp*, *klirp*). CELEX bigram token frequency was matched on average for the substitution and migration neighbours (substitution $M = 997.12$, $SD = 678.09$; migration $M = 1058.08$, $SD = 584.91$). As with the words, each pseudoword's substitution neighbour and migration neighbour was used to create the foil letters in the letter identity and letter position condition respectively. For example, if the word *blire* was presented and the fourth position cued, *r* would be the correct letter, *d* would be the foil in the letter identity condition, and the letter *l* would be the foil in the letter position condition.

Illegal nonwords were created in the same way as the word and pseudoword items. Only consonants were included in the string, and care was taken to ensure that commonly contiguous letters (e.g., *sh*) were not present. Words, pseudowords and illegal nonwords were intermixed and randomized for each participant.

Procedure. The Reicher-Wheeler task was administered to participants using DMDX software (Forster & Forster, 2003). Stimuli were presented in lower-case in black courier-new font on a light grey background. On each trial, participants saw a fixation cross for approximately 2000ms (119 ticks at 16.70ms per tick), followed by the target for 284ms (17 ticks). This timing was decided through careful consideration of previous

research, and was confirmed to be appropriate based on pilot data. Each letter of the target was then simultaneously backward masked by a hashmark. The target and foil letters were presented above and below one of the hashmarks in the string. The probed position was always a letter that was internal to the string (i.e., exterior letters such as *s* and *e* in *slime* were never probed). The probed position was randomized across trials such that participants were unable to attend to a single letter position to solve the task. Participants were told to respond as accurately and as quickly as they could, using the arrow buttons on the keyboard, as to whether the top or the bottom letter had appeared in the letter string at the position probed. The two-alternative forced choice task remained on the screen until a response was made. Four versions of the task were created to ensure that participants only saw each item once in a single condition². Participants received a practice block of 12 items before commencing the 48 experimental trials (24 identity trials, 24 position trials; 16 word trials, 16 pseudoword trials, 16 illegal nonword trials).

Results and Discussion

Nine participants who were at ceiling (100% accuracy) for trials in the condition-pairs most critical to addressing our research question (i.e., letter identity task: words vs pseudowords, pseudowords vs illegal nonwords; letter position task: words vs pseudowords, pseudowords vs illegal nonwrods) were removed from the analyses.

Responses with reaction times less than 200ms were removed from the analysis (< 1% of trials). To investigate the influence of orthographic knowledge on task performance we created three groups based on participants' absolute irregular word reading score (low-, intermediate- and high- orthographic knowledge; 24 participants in each group).

Participants' age and irregular word reading scores on the CC2 were correlated, $r = .40$, $p < .01$, resulting in the three groups differing both on absolute irregular word reading score,

² This task formed part of a larger study. We created four rather than two versions of the task in order to accommodate with other tasks that were administered during the same testing session.

$F(2, 29.72) = 80.31, p < .001$, and age, $F(2, 69) = 12.76, p < .001$ (see Table 1). No attempts were made to partial out the influence of age from irregular word reading in the analyses as our intention was not to compare those with poor orthographic knowledge (for their age) to those with good orthographic knowledge. Rather, our aim was to investigate the development of orthographic knowledge, and since irregular word reading is highly correlated with the amount of reading instruction and experience a child has had, removing the effect of age from the analyses would provide a somewhat superficial measure of orthographic development.

Table 1. Age and irregular word reading scores for the low, intermediate and high orthographic knowledge groups. Percentile scores are based on the CC2 age based normative data.

		Low		Intermediate		High	
		<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>
Age		8.73	1.08	9.56	1.10	10.33	1.12
Irregular word reading	<i>Raw</i>	14.25	4.75	21.21	1.22	24.79	1.32
	<i>%ile</i>	28.92	24.59	45.96	25.51	55.75	23.92

The data were analysed using logit mixed effects modelling (Jaeger, 2008). Two models were created to investigate the word and pseudoword superiority effects separately. Each model included orthographic context (words, pseudowords for WSE model; pseudowords, illegal nonwords for PSE model), group (low, intermediate, high) and task type (letter identity, letter position) as fixed effects, and was selected based on its goodness of fit to the data. Based on our hypotheses, three models for each superiority effect were tested: (1) a model including the interaction between orthographic context and group, and the interaction between orthographic context and task type, (2) a model including the interaction between orthographic context and group, the interaction between orthographic context and task type, and between group and task type, and (3) a model including the

three-way interaction between orthographic context, group and task type. All lower-level terms were also included in the models (i.e., model (1) and (2) included all main effects, and model (3) included all main effects and all two-way interactions). The models were compared pair-wise in order of complexity. Model (1) was compared to a simpler model including the interaction between orthographic context and group and a main effect of task type. Subjects and items were always included as random effects.

Word Superiority Effect (WSE). The best fitting model included the three-way interaction between orthographic context, group, and task type, $\chi^2(2) = 8.47, p < .05$. The estimates from this model are presented in Figure 1. Overall, participants performed better on the letter identity than on the letter position task, $b = .70, SE = .10, Z = 6.73, p < .0001$, and performance was better for words than for pseudowords, $b = .41, SE = .17, Z = 2.50, p < .05$. The WSE was significant for the letter identity task, $b = .57, SE = .20, Z = 2.77, p < .01$, but not for the letter position task, $b = .26, SE = .18, Z = 1.41, p = .16$. However, the size of the WSE did not differ between the two tasks, $b = .15, SE = .10, Z = 1.48, p = .14$.

For the letter identity task, the significant WSE was modulated by group, with only the high orthographic knowledge group displaying the effect (low $b = .11, SE = .27, Z = 0.43, p = .67$; intermediate $b = .35, SE = .29, Z = 1.21, p = .23$; high $b = 1.24, SE = .35, Z = 3.53, p < .001$). Furthermore, the WSE was significantly larger for the high orthographic knowledge group than for the low and intermediate groups combined, $b = .73, SE = .23, Z = 3.26, p < .01$.

For the letter position task, the WSE was marginal for the low orthographic knowledge group, $b = .49, SE = .25, Z = 1.95, p < .06$, and did not approach significance for the intermediate or high orthographic knowledge groups (intermediate: $b = .18, SE = .26, Z = .68, p = .50$; high: $b = .11, SE = .28, Z = 0.40, p = .69$). The marginal WSE for the low orthographic knowledge group did not differ significantly from the intermediate and high group combined, $b = .32, SE = .19, Z = 1.70, p = .09$.

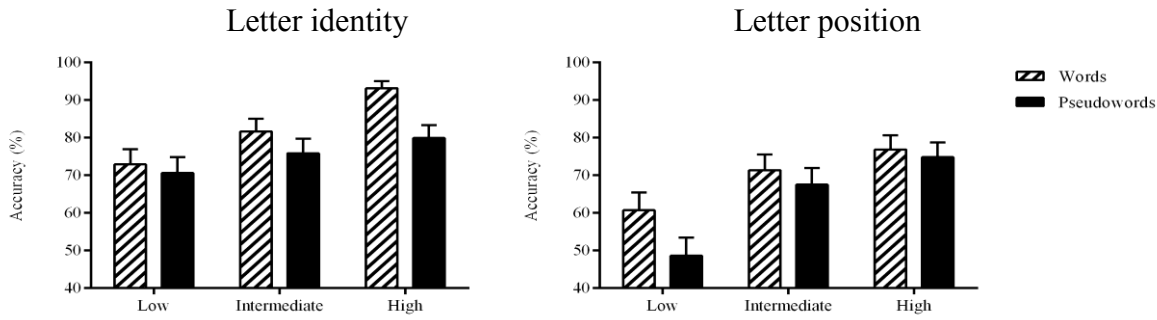


Figure 1. Model estimates of the mean accuracy scores for words and pseudowords as a function of orthographic knowledge group (low, intermediate and high) and task type (letter identity and letter position). Error bars denote the standard error of the mean.

Pseudoword Superiority Effect (PSE). The best fitting model included the interaction between orthographic context and task type, and the interaction between orthographic context and group, $\chi^2(1) = 12.48, p < .01$. While the most complex model including the three-way interaction did not provide the best fit to the data ($p > .17$), the estimates for this model are presented in Figure 2, so as to not obscure potential non-significant trends in the data, and to enable direct comparison to the WSE presented in Figure 1.

Performance was better for the letter identity task than the letter position task, $b = .26, SE = .09, Z = 2.92, p < .01$, and better for pseudowords than for illegal nonwords, $b = .64, SE = .13, Z = 4.85, p < .0001$. Follow-up of the interaction between orthographic context and task type revealed that the PSE was significant for both the letter identity, $b = .93, SE = .16, Z = 5.69, p < .0001$, and position task, $b = .36, SE = .16, Z = 2.27, p < .05$, but was significantly larger for the letter identity task, $b = .29, SE = .09, Z = 3.16, p < .01$.

The interaction between orthographic context and group was followed up by looking at the size of the PSE for each orthographic knowledge group. Because the three-way interaction between orthographic context, group and task type did not significantly

improve the fit of the model, we were not justified to investigate the interaction between orthographic context and group for each task type separately. Planned comparisons revealed that the PSE (collapsed across task) was significant for the intermediate, $M = 15\%$; $b = .69$, $SE = .18$, $Z = 3.71$, $p < .001$, and high orthographic knowledge group, $M = 21\%$; $b = 1.01$, $SE = .19$, $Z = 5.34$, $p < .0001$, but not for the low group, $M = 5\%$; $b = .23$, $SE = .18$, $Z = 1.31$, $p = .19$. Furthermore, the PSE was significantly larger for the intermediate and high group combined relative to the low group, $b = .54$, $SE = .13$, $Z = 4.01$, $p < .001$ ³.

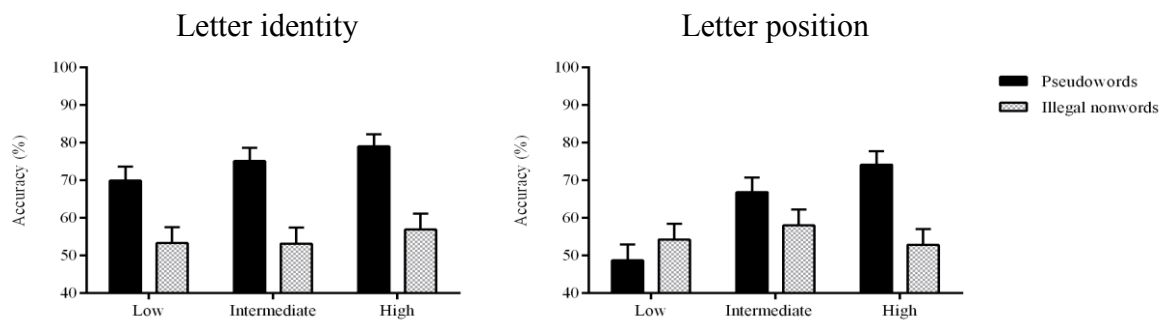


Figure 2. Model estimates of the mean accuracy scores for pseudowords and illegal nonwords as a function of orthographic knowledge group (low, intermediate and high) and task type (letter identity and letter position). Estimates are based on the model including the three-way interaction between orthographic knowledge group, orthographic context, and task type. Note that the pseudoword condition reflected in this figure is the same as in Figure 1, however, the means are slightly different as they are estimated from different models.

³ As previously noted, we opted not to include age in the analyses. Note, however, that the planned contrasts involving the three orthographic knowledge groups reported in this study were very similar when the contrasts were based on the same final model except including age (and its appropriate interactions) as a fixed factor.

The findings regarding the PSE were straightforward. The effect was larger for the letter identity task than for the letter position task, indicating that orthotactic constraints play a more prominent role in accurate letter identity processing than in letter position processing during the primary school years. Furthermore, the PSE (collapsed across task) was significantly larger for participants with high and intermediate orthographic knowledge than for those with low orthographic knowledge, suggesting that the influence of orthotactic constraints on letter processing increases as orthographic knowledge develops.

The pattern of results regarding the WSE was more complex. For the letter identity task, there was a significant WSE, which was driven by the high orthographic knowledge group, who were the only group in the sample to display the effect. This finding suggests that there is an influence of a child's whole-word orthographic representations on letter identification and that this influence increases as orthographic knowledge develops. This pattern was not observed for the letter position task. Collapsed across group, there was no significant WSE, indicating that whole-word orthographic representations have little influence on a child's ability to process letter position during the primary school years.

Two alternative hypotheses follow from this finding. It may be that whole-word orthographic representations simply do not influence letter position processing, regardless of how advanced a reader's orthographic knowledge is. Alternatively, a reader's whole-word orthographic representations may influence letter position processing, but this influence is delayed relative to letter identity processing, such that the WSE on the letter position task only emerges in well-advanced readers with over a decade of reading experience. This hypothesis was tested in Experiment 2 by administering the Reicher-Wheeler task to a sample of skilled adult readers.

Experiment 2

Method

Participants. Participants were 60 undergraduate students (25 males) from Macquarie University, Australia, who took part in the study in exchange for either course credit or monetary reward.

Task items and procedure. The task items were the same as those administered in Experiment 1 to the children. Two versions of the task were created to ensure that participants saw each letter-string only once on a single condition. The only major difference between the adult task and the task administered to the children in Experiment 1 was the presentation duration of the letter-string. As is typically done with adults to avoid ceiling effects on the Reicher-Wheeler task, the presentation duration of the item was predetermined for each participant by a preliminary test phase (e.g., Grainger et al., 2003). Based on their performance on the preliminary test phase, most participants ($N = 41$) were presented with the item for 33ms (2 ticks, 16.70ms per tick) in the experimental phase (range = 17-50ms; 1-3 ticks). This presentation duration is similar to previous Reicher-Wheeler studies with skilled adult readers (e.g., Chase & Tallal, 1990; Coch & Mitra, 2010; Grainger et al., 2003; Lété & Ducrot, 2008).

Results and Discussion

Responses with reaction times less than 200ms were removed from the analysis (< 1% of trials). We tested two models, including (1) the main effect of orthographic context and task type, and (2) the interaction between orthographic context and task type. Model (2) was tested against model (1), and model (1) was tested against a model including the main effect of orthographic context only. Subjects and items were included in the analyses as random effects. The estimates for the most complex WSE and PSE model (model 2) are presented in Figure 3.

Word Superiority Effect (WSE). The best fitting model included the main effects

of orthographic context and task type, $\chi^2(1) = 44.26$, $p < .0001$. Including the interaction between orthographic context and task type did not provide a better fit to the data ($p > .94$). Performance was significantly better for the letter identity task than for the letter position task, $b = .51$, $SE = .08$, $Z = 6.64$, $p < .0001$, and better for words than for pseudowords, $b = .52$, $SE = .14$, $Z = 3.63$, $p < .001$.

Pseudoword Superiority Effect (PSE). The best fitting model included the interaction between orthographic context and task type, $\chi^2(1) = 7.23$, $p < .01$. Performance was significantly better for the letter identity than for the letter position task, $b = .28$, $SE = .07$, $Z = 4.05$, $p < .001$, and better for pseudowords than for illegal nonwords, $b = .65$, $SE = .13$, $Z = 5.04$, $p < .0001$. The PSE was significant for both the letter identity, $b = .84$, $SE = .15$, $Z = 5.65$, $p < .0001$, and position task, $b = .47$, $SE = .15$, $Z = 3.22$, $p < .01$, but was significantly larger for the letter identity task, $b = .19$, $SE = .07$, $Z = 2.69$, $p < .01$.

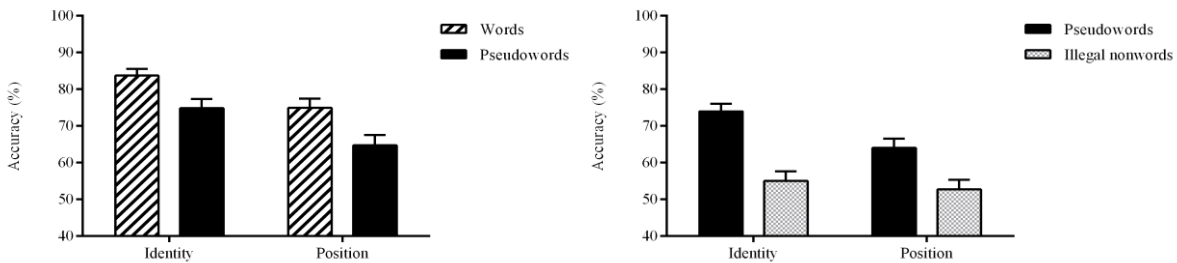


Figure 3. Model estimates of the mean accuracy scores for words and pseudowords, and pseudowords and illegal nonwords as a function of task type (letter identity and letter position). Error bars indicate the standard error of the mean. Note that the pseudoword condition reflected in the two graphs are the same, however, the means are slightly different as they are estimated from different models.

As was found in Experiment 1, the PSE was significantly larger for the letter identity task than for the letter position task, suggesting that orthotactic constraints have a greater influence on letter identity processing than on letter position processing in both

children and adults. The critical finding from Experiment 2 was that the WSE was present for both the letter identity and the letter position task. Furthermore, the WSE did not differ between the two tasks, indicating that whole-word orthographic representations influence letter identity and position processing similarly in skilled adult readers.

General Discussion

The present study investigated the influence of higher-level orthographic knowledge on letter identity and position processing. The influence of two components of orthographic knowledge on letter processing were explored: a reader's stored whole-word orthographic representations for specific words (as measured by the WSE), and a reader's knowledge of orthotactic constraints (as measured by the PSE). Whether or not these two higher-level influences on letter processing become more prominent as orthographic knowledge develops was tested by looking at the relationship between the size of the WSE and PSE and irregular word reading performance. The results indicate that letter identity and position processing are differentially influenced by orthographic knowledge. Specifically, knowledge of orthotactic constraints facilitates letter identity processing more so than letter position processing both for children and adults, and the influence of a reader's whole-word orthographic representations on letter position processing appears to be delayed relative to letter identity processing.

The Word Superiority Effect (WSE)

Our hypothesis that the WSE for the standard letter identity task would emerge with the development of orthographic knowledge was supported. Specifically, we found that the WSE for the letter identity task was only significant for children in the high orthographic knowledge group in Experiment 1, and for the skilled adult readers in Experiment 2. This finding is consistent with L  t   and Ducrot (2008), who found a significant WSE for adults but not for 6 and 7 year old readers, and with Grainger et al. (2003), who found a small WSE for older children (mean age = 11.5 years) and adults.

Together with previous studies, our findings suggest that the presence of whole-word orthographic representations exerts an influence on the process of letter identification, and that this influence increases as orthographic knowledge develops.

In contrast to the letter identity task, the WSE for the letter position task did not increase across the three developmental groups in Experiment 1. Following this finding, we formed two alternative hypotheses to be tested in Experiment 2. One hypothesis is that whole-word orthographic representations never influence letter position processing, regardless of how advanced a reader's orthographic knowledge is. Alternatively, the influence of a reader's whole-word orthographic representations may be delayed relative to letter identity processing, such that the WSE on the letter position task emerges only for skilled adult readers who have had over a decade of reading experience. The findings from Experiment 2 provided evidence for the latter hypothesis. Skilled adult readers not only displayed a significant WSE for the letter position task, but the magnitude of the effect was equivalent to the WSE for the letter identity task.

These findings indicate that the precision of a reader's orthographic representations, rather than just their existence, influences letter position processing. While it is theoretically impossible for the WSE to emerge if the written words in the experiment are unknown to participants, simply knowing the written words does not appear to be enough to produce a significant WSE in the letter position task. The same words were used in the letter identity and letter position tasks. Therefore, if just knowing a written word facilitates letter position processing, then the children in the high orthographic knowledge group should have displayed a significant WSE for both the letter identity and the letter position tasks. This was not the case. Instead the WSE for the letter position task was delayed relative to the letter identity task, consistent with the idea that the quality of a reader's whole-word orthographic representations plays a critical role in their influence over letter position processing. This interpretation is in line with recent findings from

skilled adult readers showing that letter position processing is influenced by the precision of a reader's orthographic representations, where precise representations are fully rather than partially specified, enabling a written word to directly activate its matching orthographic representation with minimal competition from visually similar words (Andrews & Lo, 2012, see also Perfetti, 1992; Perfetti, 2007 and Ehri, 2005).

The finding that the WSE for the letter position task was present for adults but not for primary school readers has important implications for future research. Most studies attempting to map the developmental trajectory of letter position processing – including the present study – have investigated letter position processing in primary school children and skilled adult readers (e.g., Acha & Perea, 2008; Castles et al., 2007; Grainger et al., 2012; Lété & Fayol, 2012; Paterson et al., 2015; Perea & Estevez, 2008). To our knowledge, no study has looked at how letter position processing develops between the age of 12 and 18 years. Our findings suggest that critical changes in the way that orthographic knowledge influences letter position processing occur during this time period. We therefore encourage future research to explore letter position processing in adolescents, with the hope that this will provide a more comprehensive understanding of letter position processing across development.

It is important to recognize that the exact cognitive mechanisms underpinning the WSE are still widely debated, making it difficult to fully interpret the findings from the present study within existing theories. The WSE can be explained using two alternative theories. One theory uses feedback from the word to the letter level of representation to explain the effect. Specifically, activation of a word's orthographic representation at the word level feeds back to the letter level, reinforcing the activation of the word's component letter representations (McClelland & Rumelhart, 1981). An alternative theory uses cascaded activation to the word level to explain the effect. For example, Grainger and Jacobs' dual read-out model (1994) proposes that letters can be identified by either the

activation of the letter representations (letter readout) or can be inferred following word identification (word readout). The WSE reflects the advantage of having an additional word readout function that can be drawn upon when individual letter readout fails.

Whilst the findings from the present study do not enable us to distinguish between these two theories, they do enable us to draw conclusions in regards to the potential role that the feedback mechanism between the word and letter level might play in the WSE across development. Following the theory that the WSE is the result of feedback from the word to the letter level, it could be argued that the increasing word superiority effect across development is not driven by changes within a reader's lexicon per se, but by a strengthening of the feedback mechanism. The findings from this study suggest that this is not the case. Indeed, if the increasing word superiority effect across development was caused by the strengthening of the feedback mechanism, then the developmental trajectory of the WSE should have been similar for the letter identity and position tasks.

The Pseudoword Superiority Effect (PSE)

In contrast to the WSE findings, the developmental trajectory of the PSE was similar for the letter identity and position tasks. In Experiment 1, the PSE increased across the three orthographic knowledge groups, indicating that the influence of orthotactic constraints on letter identity and position processing increases as orthographic knowledge develops. Interestingly, the primary school children showed a larger PSE for the letter identity task than for the letter position task – a finding that was replicated in Experiment 2 with skilled adult readers. That both children and adults showed this effect suggests that the greater influence of orthotactic constraints on letter identity processing relative to letter position processing is a characteristic of the visual word recognition system that remains stable across development.

Like the WSE the exact mechanisms underlying the PSE are currently unclear. One school of thought is that the PSE is driven by the same processes as the WSE – that is,

either by feedback from the word to letter level, or cascaded activation to the word level (Grainger & Jacobs, 1994; McClelland & Rumelhart, 1981). The pseudoword partially activates its real-word neighbours (e.g., *toble* would activate *table*), resulting in a pseudoword advantage over illegal nonwords. An alternative account is that the PSE reflects perceptual fluency that is produced by stimulus familiarity independently of lexical status. This perceptual fluency may arise due to the pronounceability of the pseudoword (Ziegler & Jacobs, 1995) or the uniquely orthographic aspects of the pseudoword, such as frequency of letter combinations (Grainger et al., 2003).

The finding that many of the children in the sample displayed a PSE in the absence of a WSE presents challenges to models that propose a lexical locus for the PSE, such as the interactive-activation model (McClelland & Rumelhart, 1981) and the dual read-out model (Grainger & Jacobs, 1994). According to these models this dissociation between the WSE and the PSE should not occur, as words always activate their matching orthographic representations more so than pseudowords (Grainger et al., 2003). Based on a similar dissociation with a developmental sample, Grainger et al (2003) concluded that the PSE must be driven by perceptual fluency rather than lexical influences.

However, the present results do not entirely rule out a lexical locus for the PSE. It could be that the same mechanisms underpin the WSE and PSE, but that for novice readers, both words and pseudowords produce dispersed activation within the lexicon, resulting in multiple orthographic representations being activated simultaneously. This proposition can account for a significant advantage for pseudowords over illegal nonwords (pseudowords activate visually similar words more so than illegal nonwords), and no advantage for words over pseudowords (both words and pseudowords activate many visually similar words). This interpretation is also supported by the finding that the participants with the most advanced orthographic knowledge in the present study showed both a WSE and PSE. These participants are likely to have well-developed and precise

orthographic representations, resulting in written words directly activating their matching orthographic representations, and hence providing an advantage for words over pseudowords.

Conclusion

The findings from the present study indicate that a reader's whole-word orthographic representations and their knowledge of orthotactic constraints influence both letter identity and letter position processing. How these higher-order influences play out as orthographic knowledge develops, however, differs for letter identity and position processing. Specifically, the influence of a reader's whole-word orthographic representations on letter position processing appears to be comparatively delayed, supporting the idea that the ongoing development of precision in a reader's orthographic representations strongly influences accurate letter position processing. These findings not only provide various challenges to models of visual word recognition, but also suggest that future studies investigating the development of letter identity and position processes must consider the role that an individual's higher-level orthographic knowledge may have on these lower-level processes.

References

- Acha, J., & Perea, M. (2008). The effects of length and transposed-letter similarity in lexical decision: Evidence with beginning, intermediate, and adult readers. *British Journal of Psychology*, 99, 245-264. doi: 10.1348/000712607X224478
- Andrews, S., & Lo, S. (2012). Not all skilled readers have cracked the code: individual differences in masked form priming. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 38(1), 152-163. doi: 10.1037/a0024953
- 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
- Castles, A., Davis, C., Cavalot, P., & Forster, K. (2007). Tracking the acquisition of orthographic skills in developing readers: Masked priming effects. *Journal of Experimental Child Psychology*, 97, 165-182. doi:10.1016/j.jecp.2007.01.006
- Chase, C. H., Tallal, P. (1990). A developmental, interactive activation model of the word superiority effect. *Journal of Experimental Child Psychology*, 49, 448-487.
- Coch, D., Mitra, P. (2010). Word and pseudoword superiority effects reflected in the ERP waveform. *Brain Research*, 1329, 159-174. doi:10.1016/j.brainres.2010.02.084
- Ehri, L. C. (2005). Learning to read words: Theory, findings, and issues. *Scientific Studies of Reading*, 9(2), 167-188.
- Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers*, 35(1), 116-124.
- Friedmann, N., Dotan, D., and Rahamim, E. (2010). Is the visual analyzer orthographic-specific? Reading words and numbers in letter position dyslexia. *Cortex*, 46(8), 982-1004. doi:10.1016/j.cortex.2009.08.007

- Friedmann, N., and Haddad-Hanna, M. (2012). Letter position dyslexia in Arabic: From form to position. *Behavioural Neuropsychology* 25, 193-203, doi: 10.3233/BEN-2012-119004. doi:10.3233/BEN-2012-119004
- Friedmann, N., and Rahamim, E. (2007). Developmental letter position dyslexia. *Journal of Neuropsychology* 1, 201-236. doi: 10.1348/174866407X204227
- Frost, R. (2012). Towards a universal model of reading. *Behavioural and Brain Sciences*, 35(5), 263-279. doi: <http://dx.doi.org/10.1017/S0140525X11001841>
- Gomez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: a model of letter position coding. *Psychological Review*, 115(3), 577. doi: 10.1037/a0012667
- Grainger, J., Bouttevin, S., Truc, C., Bastien, M., & Ziegler, J. (2003). Word superiority, pseudoword superiority, and learning to read: A comparison of dyslexic and normal readers. *Brain and Language*. 87, 432-440. doi: 10.1016/S0093-934X(03)00145-7
- Grainger, J., & Jacobs, A. M. (1994). A dual read-out model of word context effects in letter perception: Further investigations of the word superiority effect. *Journal of Experimental Psychology: Human Perception and Performance*, 20(6), 1158-1176
- Grainger, J., L  t  , B., Bertrand, D., Dufau, S., Ziegler, J. C. (2012). Evidence for multiple routes in learning to read. *Cognition*, 123, 280-292. doi: 10.1016/j.cognition.2012.01.003
- Grainger, J., & Ziegler., J. C. (2011). A dual-route approach to orthographic processing. *Frontiers in Psychology*, 2(54), 1-13, doi: 10.3389/fpsyg.2011.00054
- Jaeger, T. F. (2008). Categorical Data Analysis: Away from ANOVAs (transformation or not) and towards Logit Mixed Models. *Journal of Memory and Language*, 59(4), 434-446. doi: 10.1016/j.jml.2007.11.007
- Johnston, J. C., & McClelland, J.L. (1974). Perception of letters in words: seek not and eye shall find. *Science*, 184, 1192-1194.

- Juola, J. F., Schadler, M., Chabot, R. J., & McCaughey, M. W. (1978). The development of visual information processing skills related to reading. *Journal of Experimental Child Psychology*, 25(3), 459-476. doi: 10.1016/0022-0965(78)90069-3
- Kinoshita, S., Castles, A., & Davis, C. (2009). The role of neighbourhood density in transposed-letter priming. *Language and Cognitive Processes*, 24(4), 506-526. doi: 10.1080/01690960802289213
- Kezilas, Y., Kohnen, S., McKague, M., Castles, A. (2014). The locus of impairment in developmental letter position dyslexia. *Frontiers in Human Neuroscience*, 8(356), 1-14. doi: 10.3389/fnhum.2014.00356
- Lété, B., Ducrot, S. (2008). Visuo-attentional processing by dyslexic readers on the Reicher-Wheeler task. *Current Psychology Letters*, 24(1), 25-40
- McClelland, J. L., Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review*, 88, 375-407
- Friedmann, N., Gvion, A., & Nisim, R. (2015). Insights from letter position dyslexia on morphological decomposition in reading. *Frontiers in Human Neuroscience*, 9(143), doi: 10.3389/fnhum.2015.00143
- Kohnen, S., & Castles, A. (2013). Pirates at parties: Letter position processing in developing readers. *Journal of Experimental Child Psychology*, 50(14), 3681-3692. doi: <http://dx.doi.org/10.1016/j.jecp.2012.08.011>
- Kohnen, S., Nickels, L., Castles, A., Friedmann, N., McArthur, G. (2012). When ‘slime’ becomes ‘smile’: developmental letter position dyslexia in English. *Neuropsychologia*, 50(14), 3681-3692. doi: 10.1016/j.neuropsychologia.2012.07.016
- Lupker, S. J., & Davis, C. J. (2009). Sandwich priming: a method for overcoming the limitations of masked priming by reducing lexical competitor effects. *Journal of*

- Experimental Psychology: Learning, Memory and Cognition*, 35(3), 618-639. doi: 10.1037/a0015278
- Lupker, S. J., Perea, M., & Davis, C. (2008). Transposed-letter effects: Consonants, vowels and letter frequency. *Language and Cognitive Processes*, 23(1), 93-116. doi: 10.1080/01690960701579714
- Paterson, K. B., Read, J., McGowan, V. A., Jordan, T. R. (2014). Children and adults both see 'pirates' in 'parties': letter-position effects for developing readers and skilled adult readers. *Developmental Science*, 18(2), 1-9. doi: 10.1111/desc.12222
- 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. doi: 10.1080/09541440701306941
- Perea, M., & Lupker, S. J. (2003). Transposed-letter confusability effects in masked form priming. In S. Kinoshita and S. J. Lupker (Eds.), *Masked priming: State of the art*. Hove, UK: Psychology Press.
- 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. doi:10.1016/j.jml.2004.05.005
- Perfetti, C. A. (1992). The representation problem in reading acquisition. In P. B. Gough, L.C. Ehri, & R. Treiman (Eds.), *Reading acquisition*. Hillsdale, NJ: Erlbaum.
- Perfetti, C. A. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading*, 11(4), 357-383. doi:10.1080/10888430701530730
- Rayner, K., White, S. J., Johnson, R. L., & Liversedge, S. P. (2006). Reading words with jumbled letters: There is a cost. *Psychological Science*, 17, 192-193. doi: 10.1111/j.1467-9280.2006.01684.x
- Reicher, G. M. (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology*, 81, 275-280

- Reilhac, C., Jucla, M., Iannuzzi, S., Valdois, S., & Démonet, J. (2012). Effect of orthographic processes on letter identity and letter-position encoding in dyslexic children. *Frontiers in Psychology*, 3, 1-11. doi: 10.3389/fpsyg.2012.00154
- Wheeler, D. D. (1970). Processes in word recognition. *Cognitive Psychology*, 1, 59-85. doi: [http://dx.doi.org/10.1016/0010-0285\(70\)90005-8](http://dx.doi.org/10.1016/0010-0285(70)90005-8)
- Ziegler, J. C., Bertrand, D., Lété, B., & Grainger, J. (2014). Orthographic and phonological contributions to reading development: Tracking developmental trajectories using masked priming. *Developmental Psychology*, 50(4), 1026-1036. doi: 10.1037/a0035187
- Ziegler, J. C., & Jacobs, A. M. (1995). Phonological information provides early sources of constraint in the processing of letter strings. *Journal of Memory and Language*, 34(5), 357-593. doi: 10.1006/jmla.1995.1026

Appendix

Word stimuli used in the Reicher-Wheeler task

LETTER IDENTITY		LETTER POSITION	
Target	Distractor	Target	Distractor
b <u>e</u> ings	brings	b <u>e</u> ings	begins
h <u>a</u> res	hires	h <u>a</u> res	hears
po <u>l</u> os	poles	po <u>l</u> os	pools
s <u>n</u> ug	slug	s <u>n</u> ug	sung
bo <u>l</u> t	boat	bo <u>l</u> t	bolt
fi <u>l</u> ed	fixed	fi <u>l</u> ed	field
tr <u>a</u> p	trip	tr <u>a</u> p	tarp
cl <u>a</u> ms	claps	cl <u>a</u> ms	calms
si <u>n</u> ks	silks	si <u>n</u> ks	skins
da <u>i</u> ry	daisy	da <u>i</u> ry	diary
si <u>g</u> ns	sighs	si <u>g</u> ns	sings
sl <u>i</u> me	slide	sl <u>i</u> me	smile
fe <u>e</u> ls	feeds	fe <u>e</u> ls	flees
st <u>a</u> in	slain	st <u>a</u> in	satin
fa <u>r</u> med	formed	fa <u>r</u> med	framed
se <u>a</u> ls	seats	se <u>a</u> ls	sales
sp <u>i</u> ne	shine	sp <u>i</u> ne	snipe
ti <u>r</u> ed	timed	ti <u>r</u> ed	tried
sn <u>i</u> ps	slips	sn <u>i</u> ps	spins
ma <u>l</u> es	makes	ma <u>l</u> es	meals
wi <u>r</u> ed	wiped	wi <u>r</u> ed	weird
bo <u>w</u> ls	boils	bo <u>w</u> ls	blows
wa <u>r</u> ps	warns	wa <u>r</u> ps	wraps
da <u>r</u> ed	dated	da <u>r</u> ed	dread

Appendix cont.

Pseudoword stimuli used in the Reicher-Wheeler task

LETTER IDENTITY		LETTER POSITION	
Target	Distractor	Target	Distractor
ber <u>g</u> s	berks	b er <u>g</u> s	bre <u>g</u> s
kir <u>l</u> p	kirmp	kir <u>l</u> p	klirp
keab <u>s</u>	keals	keab <u>s</u>	kabes
fir <u>t</u> h	firch	fir <u>t</u> h	frith
blir <u>e</u>	blide	blir <u>e</u>	brile
s <u>k</u> ole	smole	s <u>k</u> ole	sloke
ke <u>i</u> ngs	koings	ke <u>i</u> ngs	ke <u>g</u> ins
seta <u>g</u>	semag	seta <u>g</u>	sateg
smu <u>l</u> e	smupe	smu <u>l</u> e	slume
sta <u>l</u> if	shalif	sta <u>l</u> if	slatif
sme <u>p</u>	snep	sme <u>p</u>	semp
gar <u>t</u> h	garsh	gar <u>t</u> h	grath
bro <u>g</u>	brug	bro <u>g</u>	borg
pa <u>r</u> ld	porld	pa <u>r</u> ld	plard
trom <u>s</u>	trog	trom <u>s</u>	torms
pi <u>l</u> ch	polch	pi <u>l</u> ch	plich
gar <u>p</u> s	garts	gar <u>p</u> s	graps
sne <u>h</u>	stech	sne <u>h</u>	sench
fi <u>r</u> nch	fornch	fi <u>r</u> nch	frinch
fr <u>i</u> sh	frich	fr <u>i</u> sh	firsh
s <u>p</u> uts	snuts	s <u>p</u> uts	stups
gor <u>l</u> t	gormt	gor <u>l</u> t	glort
fald <u>s</u>	falms	fald <u>s</u>	flads
glea <u>d</u>	gload	glea <u>d</u>	galed

Appendix cont.**Illegal nonword stimuli used in the Reicher-Wheeler task**

LETTER IDENTITY		LETTER POSITION	
Target	Distractor	Target	Distractor
x <u>m</u> vqw	xnvqw	mvq <u>w</u> z	mvwqz
zxq <u>k</u> n	zxqcn	jz <u>x</u> qk	jxzqk
wf <u>g</u> qz	wfpqz	wf <u>g</u> qz	wqfgz
fxq <u>w</u> j	fxqzj	fxq <u>w</u> j	fxwqj
bf <u>k</u> j	bfdj	bf <u>k</u> j	bkfj
xq <u>t</u> vw	xqnvw	xq <u>t</u> vw	xtqvw
kz <u>x</u> gt	kjxgt	kz <u>x</u> gt	kgzxt
lx <u>b</u> zn	lxvzn	lx <u>b</u> zn	lxzbn
qd <u>s</u> w	qdzw	qd <u>s</u> w	qsdw
nj <u>x</u> lv	njtlv	nj <u>x</u> lv	nxjlv
ncq <u>y</u> b	ncqpb	nc <u>q</u> vb	nqcvb
tz <u>d</u> jp	tzgjp	tz <u>d</u> jp	tjdzp
g <u>c</u> njl	gknjl	g <u>c</u> njl	gjcnl
sq <u>q</u> jz	sqqvz	sq <u>q</u> jz	sqxjz
cg <u>j</u> td	cgwtd	cg <u>j</u> td	ctgjd
jz <u>k</u> qg	jzfqg	jz <u>k</u> qg	jzqkg
zbp <u>x</u> v	zbphv	zbp <u>x</u> v	zxpbv
rt <u>w</u> x	rzwx	rt <u>w</u> x	rwtx
px <u>d</u> zg	pxwzg	px <u>d</u> zg	pdxzg
rv <u>z</u> xk	rgzxk	rv <u>z</u> xk	rxvzk
ptk <u>y</u> n	ptksn	ptk <u>y</u> n	ptkn
jz <u>w</u> pq	jzfpq	jz <u>w</u> pq	jwpzq
dt <u>z</u> kj	dqzkj	dt <u>z</u> kj	dzktj
xz <u>l</u> cg	xzvcg	xz <u>l</u> cg	xlczg

Chapter 5

The Locus of Impairment in English Developmental Letter Position Dyslexia

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Abstract

Many children with reading difficulties display phonological deficits and struggle to acquire non-lexical reading skills. However, not all children with reading difficulties have these problems, such as children with selective letter position dyslexia (LPD), who make excessive migration errors (such as reading *slime* as “smile”). Previous research has explored three possible loci for the deficit – the phonological output buffer, the orthographic input lexicon, and the orthographic-visual analysis stage of reading. While there is compelling evidence against a phonological output buffer and orthographic input lexicon deficit account of English LPD, the evidence in support of an orthographic-visual analysis deficit is currently limited. In this multiple single-case study with three English-speaking children with developmental LPD, we aimed to both replicate and extend previous findings regarding the locus of impairment in English LPD. First, we ruled out a phonological output buffer and an orthographic input lexicon deficit by administering tasks that directly assess phonological processing and lexical guessing. We then went on to directly assess whether or not children with LPD have an orthographic-visual analysis deficit by modifying two tasks that have previously been used to localize processing at this level: a same-different decision task and a nonword reading task. The results from these tasks indicate that LPD is most likely caused by a deficit specific to the coding of letter positions at the orthographic-visual analysis stage of reading. These findings provide further evidence for the heterogeneity of dyslexia and its underlying causes.

The Locus of Impairment in English Developmental Letter Position Dyslexia

Introduction

The last three decades have seen an emphasis on the role that impaired phonological processing plays in developmental dyslexia. Various researchers have posited that at the core of dyslexia lies an impairment in the ability to represent, store, and retrieve speech sounds (Stanovich, 1988; Snowling, 1998; Snowling, 2001; Ramus, 2003). This phonological deficit is proposed to be linked to the difficulty children with dyslexia experience in learning the mappings between letters and speech sounds, which is often remediated using phonics training (see Castles, Coltheart, Wilson, Valpied, & Wedgwood, 2009; McArthur, Kohnen, Larsen, Jones, Anandakumar, Banales, & Castles, 2012). The phonological deficit account of dyslexia is supported by a multitude of correlational, longitudinal, and training studies that have found developmental dyslexia to typically be associated with poor phonological awareness (e.g., Høien, Lundberg, Larsen, & Tønnessen, 1989), slow lexical retrieval skills (e.g., Denckla & Rudel, 1976), and poor verbal short-term memory (e.g., Mann, Liberman, & Shankweiler, 1980; Mann & Liberman, 1984).

However, not all children with dyslexia have a phonological impairment. For example, children with surface dyslexia appear to have no difficulties with mapping letters onto speech sounds, as is evidenced by their ability to read nonwords as proficiently as their peers (e.g., Castles & Coltheart, 1993; Broom & Doctor, 1995; Castles & Coltheart, 1996; Temple, 1997). Instead, surface dyslexics have been thought to have problems with orthographic processing, resulting in excessive reading errors where an irregular word is sounded out incorrectly using common letter-sound rules (e.g., *yacht* is read as if it rhymed with *matched*). The existence of cases of developmental dyslexia where phonological processing appears intact suggests that while some dyslexias may be attributed to an impairment in phonological processing, other dyslexias are not. Here, we provide further

evidence for the heterogeneity of dyslexia and its underlying causes by furthering the investigation of the locus of impairment in English-speaking children with developmental letter position dyslexia (LPD).

The hallmark symptom of LPD is an elevated tendency to make ‘migration errors’, where the order of letters within migratable words (more commonly known as anagrams) are confused, resulting in the misreading of a word as its migration partner (e.g., *slime* is read as “smile”). While migration errors are frequently made by beginning readers (Kohnen & Castles, 2013), English children with LPD have been found to make up to four times the number of migration errors made by their peers (Kohnen, Nickels, Castles, Friedmann, & McArthur 2012). Children with LPD have particularly high migration error rates when reading words where the transposition of letters in the middle of a word can lead to another word (e.g., *slime-smile*, *diary-dairy*). Intriguingly, cases of selective LPD have been documented, where all other reading processes appear intact (Friedmann & Rahamim, 2007; Kohnen et al., 2012). Children with selective LPD read as accurately and as fluently as their peers – except when they are asked to read migratable words.

There are four studies that have investigated the locus of impairment in developmental LPD – two in Hebrew (Friedmann & Rahamim, 2007; Friedmann, Dotan, & Rahamim, 2010a), one in Arabic (Friedmann & Haddad-Hanna, 2012), and most recently one in English (Kohnen et al., 2012). All four studies have used the cognitive model of reading aloud illustrated in Figure 1 to identify the locus of impairment in LPD. Following this model, when a word is encountered in print, its visual properties undergo orthographic-visual analysis. This stage involves identifying the word’s letters, coding the position of the letters within the word, and binding the letters to the word. Following these initial computations, the word 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 phonological output lexicon via the semantic system), and

(3) the nonlexical route (grapheme to phoneme conversion). Typically, the lexical and lexical-semantic routes successfully process all words within a reader's orthographic input lexicon (storage for familiar words), but fail to process nonwords. In contrast, the nonlexical route successfully sounds out nonwords and words that follow typical letter to sound rules ('regular words' such as *surf*, *blame* and *hand*), but fails to provide accurate pronunciation for irregular words (such as *yacht*, *come* and *friend*). According to the model, after the written input has progressed through these routes, the phonemes that make up the word are assembled and held active in the phonological output buffer until a verbal response is made.

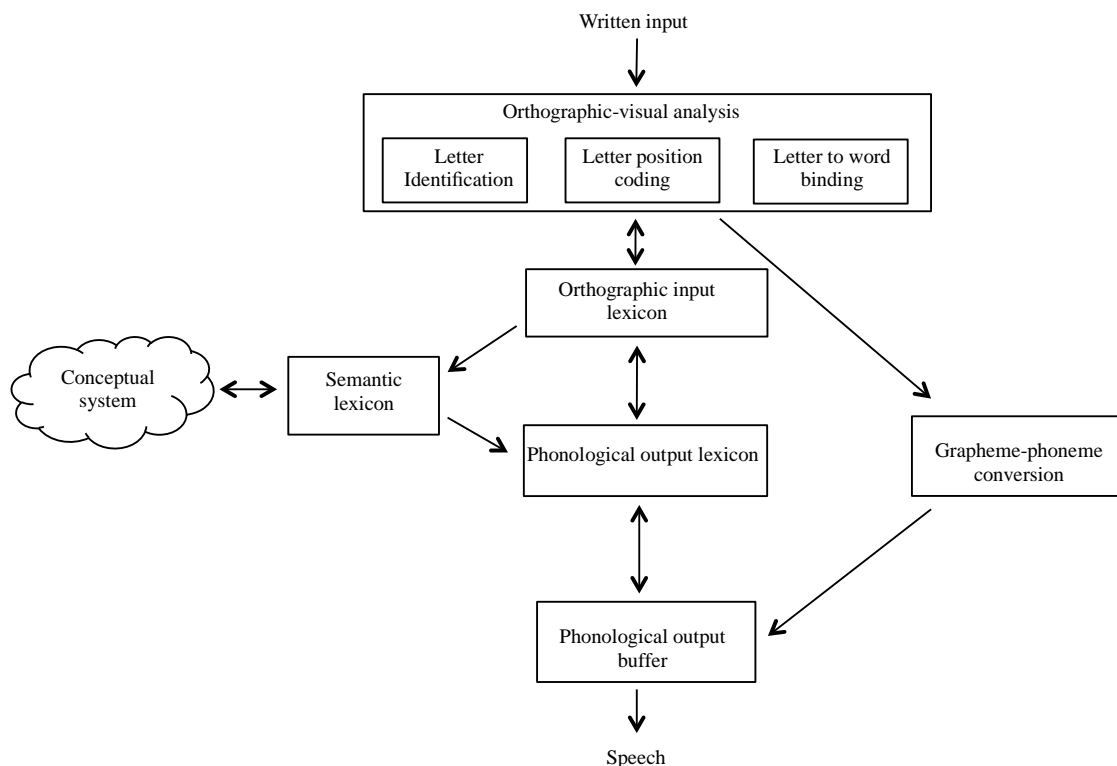


Figure 1. A cognitive model of reading aloud (e.g., Friedmann and Rahamim, 2007; Kohnen et al., 2012) detailing the three reading routes: (1) the lexical route (orthographic input lexicon to phonological output lexicon), (2) the lexical-semantic route (orthographic input lexicon to phonological output lexicon via the semantic system), and (3) the nonlexical route (grapheme to phoneme conversion). Double-headed arrows indicate feed-forward and –backward activation.

Using this model, previous research has proposed three possible loci for the migration errors seen in LPD (Friedmann & Rahamim, 2007; Kohnen et al., 2012). Firstly, the migration errors may occur at the phonological output buffer as the phonological code is being prepared for pronunciation. Strong evidence against this hypothesis comes from the observation that children with LPD perform within the average range on standardised tests that draw heavily on the phonological output buffer (e.g., phonological awareness and verbal short term memory assessments; Friedmann & Rahamim, 2007; Kohnen et al., 2012). Furthermore, Kohnen et al. (2012) reported that the majority of the migration errors made by their sample of English LPDs could not be attributed to the swapping of phonemes in the output buffer. For example, the swapping of the phonemes in *cloud* (/k/ /l/ /aw/ /d/) does not create the migration error “could” (/k/ /o/ /d/; Kohnen et al., 2012). Rather, the deficit causing this error must occur before the graphemes in the word have been converted into their appropriate phonemes.

Secondly, migration errors may occur due to an orthographic input lexicon deficit. On this account, LPDs are proposed to have fewer orthographic representations in their orthographic input lexicon than is typical for their age. When the orthographic representation matching a target word cannot be found in the lexicon, a lexical guessing strategy is adopted resulting in an error that is visually similar to the target word. This possibility is unlikely however, as LPDs have been found to read nonmigratable, irregular words (e.g., *yacht*) as proficiently as their peers, indicating that their orthographic input lexicon is intact (Friedmann & Rahamim, 2007; Kohnen et al., 2012). Furthermore, if the migration errors made by LPDs are the result of lexical guessing, they should also make other lexical similarity errors, such as substitution errors (e.g., reading *slime* as “slide”). This is not the case – their reading errors appear to be selective to the transposition of letters within words (Friedmann & Rahamim, 2007; Kohnen et al., 2012).

The third and final possibility following Figure 1 is that LPD is caused by a deficit

specific to the coding of letter positions within words at the orthographic-visual analysis stage of reading. Of the three possible deficits (phonological output buffer, orthographic input lexicon, and orthographic-visual analysis), an orthographic-visual analysis deficit currently provides the most parsimonious explanation for the available data. Two pieces of evidence suggest that LPD is caused by an orthographic-visual analysis deficit. Firstly, in Hebrew, LPDs have been found to make excessive migration errors on a same-different decision task (e.g., responding “same” to *slime-smile*; Friedmann & Rahamim, 2007; Friedmann, et al., 2010a). Two of the three cases of English LPD reported by Kohnen et al. (2012) also showed this effect. Because the same-different decision task is thought to tap prelexical processing (see Besner, Coltheart, & Davelaar, 1984; Kinoshita & Norris, 2009), LPDs’ poor performance on this task has been taken as evidence for an orthographic-visual analysis deficit (Kohnen et al., 2012). Secondly, in Hebrew, LPDs have been found to make more word responses to migratable items (e.g., reading *slime* as “smile”, and *forg* as “frog”) as well as nonword responses (e.g., reading *pilf* as “plif”), indicating that the cognitive mechanism that is defective in LPD is common to both lexical and nonlexical routes (Friedmann & Rahamim, 2007). There are two components of the model that are common to both routes: the orthographic-visual analyser and the phonological output buffer. As previously outlined, there is strong evidence refuting a phonological output buffer deficit account of LPD. Therefore, the finding that LPDs in Hebrew make more word and nonword responses to migratable items has been taken as evidence for an orthographic-visual analysis deficit, which then has knock on effects to both lexical and nonlexical reading.

There are, however, two pieces of data that appear inconsistent with an orthographic-visual analysis deficit account of English LPD. Firstly, one of the three LPD cases reported by Kohnen et al. (2012) did not make excessive migration errors on a same-different decision task. As the same-different decision task should reveal an orthographic-

visual analysis deficit, this finding may suggest that the migration errors made by this case (identified as EL) are not caused by this deficit. Secondly, while the LPDs in Kohnen et al.'s study made more word responses to migratable items (e.g., reading *slime* as “smile”, and *forg* as “frog”) than controls, they did not make more nonword migration responses than controls (e.g., reading *pilf* as “plif”). This finding proves problematic for an orthographic-visual analysis deficit account of English LPD, as a deficit at the initial, orthographic-visual analysis stage of reading should produce migration errors in both lexical and nonlexical reading. The aim of the present study was to follow up on these two unexpected findings in order to clarify the locus of impairment in English LPD.

One plausible reason why EL did not make excessive migration errors on the same-different decision task is that he was adopting a strategy during the task whereby he compared each letter across the two words. In Kohnen et al.'s (2012) task, participants were presented with two words side by side, and were given as much time as they needed to make their response. As Kohnen et al. (2012) suggested, these task conditions give participants the opportunity to compare each letter across the two words, rather than comparing the two words to one another as is intended by the task. If attention is focused on each individual letter, each letter's position is no longer processed in relation to the position of the other letters within the word. This means that letter positions will less likely be confused, and migration errors will less likely be made.

Additionally, there are two plausible reasons why the LPDs in Kohnen et al.'s (2012) study may not have made excessive nonword migration responses, where the order of letters in a nonword stimulus are confused, resulting in a nonword response (e.g., reading *pilf* as “plif”). Firstly, while letters in familiar words are thought to be processed in parallel via the lexical routes, letters in nonwords are thought to be processed serially via the nonlexical route (Rastle & Coltheart, 1998; Friedmann & Rahamim, 2007). The serial processes that underpin nonword reading might therefore reduce the likelihood that an

LPD will make nonword migration errors (Friedmann & Rahamim, 2007; Kohnen et al., 2012). Secondly, research in both Hebrew and English has shown that there are specific variables that influence whether or not LPDs make word migration errors. For example, LPDs are most likely to make a word migration error when a low frequency word can migrate into a higher frequency word via the transposition of two adjacent, internal letters (e.g., reading *trail* (frequency = 18 words per million) as ‘trial’ (frequency = 58 words per million)). It is plausible, therefore, to hypothesize that there is also a set of variables that influence whether a nonword migration error will be made, and that variation across item sets on such variables might account for differences in results.

The present study

The aim of this multiple single-case study with three English speaking LPDs was to replicate and extend previous research regarding the locus of impairment in LPD.

First, we aimed to replicate previous findings suggesting that LPD is not caused by a phonological output buffer deficit. We then sought to replicate the finding that the migration errors seen in LPD are not the result of lexical guessing due to an orthographic input lexicon deficit.

Following this, we aimed to address two findings that appear to be inconsistent with an orthographic-visual analysis deficit account of LPD. The first inconsistent finding is that EL, one of Kohnen et al.’s (2012) LPDs, did not make more migration errors on a same-different decision task than controls. The second finding that appears at odds with this account is that all three LPDs in Kohnen et al.’s (2012) study did not make more nonword migration responses (e.g., reading *pilf* as “plif”) than controls. The present study therefore aimed to extend Kohnen et al.’s (2012) study by modifying the same-different decision task and the nonword reading task in an attempt to clarify the locus of impairment. Specifically we extended Kohnen et al.’s (2012) work by (1) administering a sequential presentation variant of the same-different decision task, (2) including a

consonant-string condition in the same-different decision task, and (3) manipulating the bigram frequency of the nonwords presented in the reading aloud task.

A sequential variant of the same-different decision task was administered to eliminate a possible letter-by-letter matching strategy. That is, rather than presenting the words side by side, where a direct comparison between each word's letters can be made, we presented items one after the other. Under sequential presentation we expected all three LPDs in the present study to be significantly poorer than controls at detecting when two migratable words are different. To provide a further test of the orthographic-visual analysis deficit account of LPD, we included a consonant-string condition in the task. If LPD is due to a letter position coding deficit at the orthographic-visual analysis stage of reading, then LPDs should be poorer than controls at identifying when two migratable items are different from one another, regardless of the lexicality of the items.

In the present study we also manipulated the bigram frequency of the nonwords in the reading aloud task. One plausible reason why Kohnen et al's (2012) LPDs did not make more nonword migration errors than controls when reading aloud nonwords (e.g., reading *pilf* as "plif") is that there may be various factors that influence whether or not a nonword migration error will be made. Previous research has shown that the written frequency of a word's migration counterpart, relative to the item itself, influences whether or not a migration error will be made. For example, the most common migration error made by LPDs is the reading of a nonword (which by definition has a written frequency of 0) as a word (e.g., *coisun* is read as "cousin"). The next most common migration error is the reading of a word as its higher frequency counterpart (e.g., *trail* (frequency = 18) is read as "trial" (frequency = 58); Friedmann & Gvion, 2001). Following these findings, it is plausible to hypothesize that the bigram frequency of the nonword migration counterpart, relative to the bigram frequency of the nonword itself, will influence whether or not a nonword migration error will be made. Our exploratory hypothesis was therefore that

LPDs would be more likely to migrate a low bigram frequency nonword into its higher bigram frequency nonword counterpart (e.g., reading *plif* (bigram frequency = 180) as “pilf” (bigram frequency = 1251)), than to migrate a high bigram frequency nonword into its lower bigram frequency counterpart.

Materials and Methods

Ethics approval for this project was granted by Macquarie University Human Research Ethics Committee. Participants and their parents gave verbal and written consent to their involvement in the study.

Participants

Participants in this study were three children: LM, EL and LL. LM, was a 9 year 8 month old girl in her second semester of grade 4 when we first met her, and was homeschooled by her mother⁴. EL was a participant in Kohnen et al.’s study (2012) and was recruited for the present study when he was 9 years 8 months old and about to commence grade 5 at a mainstream school. Our third participant, LL, was an 11 year 9 month old girl who had commenced grade 7 at a mainstream school two weeks before we met her.

All three children were initially referred to us because their parents were concerned about their spelling ability. Their reading skills were reported by their parents to be within the average range for their age. Both LM and LL’s hearing and vision were reported as normal. EL had long-sightedness and astigmatism, which were corrected for with glasses. He had also been diagnosed with pendular nystagmus (involuntary repetitive rhythmic movement of eyes from side to side). All three children had no diagnoses of developmental delay or difficulties (e.g., AD(H)D, SLI).

⁴ Homeschooling for LM followed a strict and regulated curriculum matched to mainstream education. The work completed by home-schooled students has to be documented and monitored regularly.

Each LPD's performance on the standardized tests used to assess for a phonological output buffer deficit was compared to the test's age-appropriate normative data. Each LPD's performance on the experimental tasks was compared to a control group of average readers without LPD. We recruited two different grade-matched control groups. Six grade 4 controls were used as a control group for LM and EL (Age $M = 10$ years 1 month, $SD = 2$ months). Two grade 6 controls and three grade 7 controls were used as a control group for LL (Age $M = 12$ years 3 months, $SD = 7$ months).

Procedure

Participants were tested over multiple testing sessions at Macquarie University. Testing sessions went for between 90 to 150 minutes in length including breaks. All relevant property statistics for the experimental tasks were derived from N-Watch (Davis, 2005). All experimental reading aloud tasks and the visual lexical decision task were administered using flash cards. Unless otherwise specified, Crawford and Garthwaite's *t*-test (2002) was used to compare each LPD's task performance to controls, and Fisher's exact was used to compare each LPD's performance on one condition to another condition.

Results

Tests Determining Eligibility

LM, EL and LL were identified as having LPD based on their scores on the Letter Position Test (LetPos; Kohnen, Marinus, Friedmann, Anandakumar, Castles, Nickels, & McArthur, 2014). The LetPos is a reading aloud test consisting of 60 anagram words (30 anagram pairs, e.g., *slime* - *smile*), presented over two pages. There are three types of errors that can be made on this test: 'migration errors' (reading a word as its migration partner, e.g., reading *slime* as "smile"), 'word errors' (reading a word as any word other than its migration partner, e.g., reading *slime* as "slide"), and 'other errors' (reading a word as a nonword, e.g., reading *slime* as "slome"). The normative data for the LetPos was collected in the final term of the school year. LPDs were selected on the basis that their

LetPos performance was more than one standard deviation below the mean for ‘migration errors’, and within one standard deviation of the mean for ‘word errors’ and ‘other errors’, when compared to the grade-appropriate normative data.

LPD participants were also selected to have no obvious reading problems, other than the reading of migratable words. Specifically, they were selected only if they had normal irregular word and nonword reading, as assessed by the Castles and Coltheart Reading Test (CC2: Castles, Coltheart, Larsen, Jones, Saunders, & McArthur, 2009). Both LM and EL were within the average range for their age (a Z score between -1 and +1) on both the irregular word and nonword reading components of the test. While LL was within the average range on the irregular word component of the CC2, she was below average on the nonword reading component of the test⁵. She was included in the study, however, because her nonword reading errors appeared to stem from an underlying problem with reading letters in their correct order. For example, LL made nonword migration errors such as reading *borp* as “brop”. When these migration errors were removed from her score, her nonword reading was within the average range.

Control participants were selected to be average on the irregular word and nonword reading subtests of the CC2 and to be within one standard deviation of the mean on each component (migration, word and other errors) of the LetPos.

Assessing the Phonological Output Buffer

A phonological output deficit should manifest itself in poor performance on tasks that require phoneme production and/or manipulation. To investigate whether LPD is caused by a phonological output buffer deficit, LM, EL and LL were assessed on phonological awareness, speed of lexical retrieval and verbal short term and working

⁵ Note that there is currently no normative data published for children who are LL’s age (11 years 9 months). LL’s performance on the CC2, as well as that of her control group, was therefore compared to the normative data of children between the ages 11 years and 11 years 5 months.

memory. If their migration errors are caused by a phonological output buffer deficit, they should be below average on these tasks compared to age-appropriate normative data.

Phonological awareness was assessed using the Segmenting Nonwords and Phoneme Reversals subtests of the Comprehensive Test of Phonological Processing (CTOPP, Wagner, Torgesen, & Rashotte, 1999). In the Segmenting Nonwords subtest children are given a series of nonwords, which they are asked to repeat, and then say one sound at a time (e.g., “dray, d – r – ay”). In the Phoneme Reversal subtest children are asked to first repeat a nonword, and then to reverse the sounds to make it sound like a real word (e.g., “nus, sun”).

Speed of lexical retrieval was assessed using the Rapid Naming subtests of the CTOPP. LPDs were assessed on their ability to rapidly name letters, digits, objects and colours, which were each assessed separately. In these subtests, LPDs were asked to name 36 items presented on a single page as quickly as they could.

The Repetition of Nonsense Words subtest of the NEPSY (Korkman, Kirk, & Kemp, 1998) and the Digit Span subtest of the Weschsler Intelligence Scale for Children Fourth Edition (WISC-IV; Wechsler, 2003) were used to assess verbal short term and working memory. In the Repetition of Nonsense Words subtest, children are asked to repeat nonwords (e.g., *bu-lɛks-tɪs*). The Digit Span subtest has two components – Forward Digit Span, and Backwards Digit Span. In the Forward Digit Span, children are asked to repeat strings of digits in the same order as they heard them, and in the Backwards Digit Span subtest children have to repeat strings of digits in reverse order.

Table 1 shows that all LPD participants were within (or even above) the average range (Z score between -1 and +1) on all nine measures of phonological processing. In addition LM, EL and LL were asked to orally repeat the words after the experimenter for which they had previously made a migration error on in a reading aloud task. Each LPD performed this task without making a single migration error.

Taken together, these findings indicate that the migration errors made by the three LPDs in the present study cannot be attributed to a phonological output buffer deficit.

Table 1. Z scores on standardized tests used to assess for a phonological output deficit (average range is between -1 and +1)

			LM	EL	LL
Phonological awareness	Segmenting nonwords		0.33	1.67	1.67
	Phoneme reversals		0.33	0.67	-0.67
Lexical retrieval	Rapid naming	Digits	1.33	0.33	-0.67
		Letters	1.00	0.67	-1.00
		Colors	1.00	0.33	-1.00
		Objects	1.33	-0.67	-0.33
Verbal memory	Digit span	Forward	1.00	0.33	1.00
		Backward	0.00	-0.33	0.67
	Repetition of nonsense words		1.00	1.00	0.33

Assessing the Orthographic Input Lexicon

To investigate whether LM, EL and LL have an orthographic input lexicon deficit we administered a reading aloud nonmigratable, irregular words task. Irregular words were used to ensure that access to the orthographic input lexicon was obligatory for a correct response to be made. If LPDs have an orthographic input lexicon deficit, they should be poorer at this task than controls.

To explicitly test whether their excessive migration errors are the result of lexical guessing, we administered two tasks: A reading aloud migratable and substitution words task, and a visual lexical decision task. If LPDs' migration errors are the result of lexical guessing, they should make more substitution errors than controls on a reading aloud task (e.g., reading *track* as "trick"), as well as more substitution errors on a visual lexical decision task (e.g., accepting *esho* (derived from *echo*) as a word).

Reading aloud non-migratable, irregular words. Participants were asked to read aloud 87 nonmigratable words which were selected to contain at least one letter-sound rule that was atypical (e.g., pearl, cousin) according to Regcelex (Baayen, Piepenbrock, & Gulikers, 1995), a program used to compute the rule based pronunciation of a letter-string (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Because we were interested in each LPD's lexical reading skills, errors that appeared to stem from a difficulty in ordering letters in words (e.g., reading *chalk* as 'chlak') were removed from the error analysis. Both LM and EL made 12.64% errors on this task, which was not significantly different from their control group, who made 9.58% errors ($SD = 2.48\%$; $t = 1.14$, $p = 0.15$ one-tailed). LL made 6.90% errors on this task, which was not significantly different from her control group who made 8.28% errors ($SD = 2.36\%$; $t = 0.53$, $p = 0.31$ one-tailed).

Eighteen of the 87 experimental words were items that had already been administered in the irregular word reading component of the CC2. We therefore conducted an additional analysis including irregular words that were not part of the CC2 ($N = 69$). All three LPD's made as many errors as controls in this additional analysis, all $p > 0.15$ one-tailed.

This finding suggests that LM, EL and LL have as many orthographic representations in their input lexicon as controls, and that they have no difficulty in accessing these representations.

Reading aloud migratable and substitution words. Participants read aloud 58 migratable words, which were created from 29 word pairs that were different via the transposition of two internal letters (e.g., *slime-smile*). Migratable words were intermixed with 30 substitution words created from 15 pairs of words that were different via the substitution of a single internal letter (e.g., *track-trick*). Substitution words were matched as closely as possible to migratable words on length (migratable $M = 5.07$, $SD = 0.53$; substitution $M = 5.07$, $SD = 0.69$), relative written frequency between a word and its

partner (migratable $M = 27.51$, $SD = 36.83$; substitution $M = 36.61$, $SD = 36.62$), and the number of substitution neighbours (migration $M = 4.86$, $SD = 3.48$; substitution $M = 4.90$, $SD = 3.18$). The item pairs were presented over separate tasks such that participants did not read a word and its partner in the same task. These words were intermixed with 122 words, which were not used to address the research questions in the present study.

Three error types were analysed: (1) migration errors, where a migratable word was read as its partner, (2) substitution errors, where a substitution word was read as its partner, and (3) ‘N errors’, which included substitution errors (e.g., reading *slime* as “slide”), addition errors (reading *slime* as “slimes”), and deletion errors (reading *slime* as “slim”) made on all migratable and substitution words. Errors that were potentially due to sounding the word out rather than one of these three error types (e.g., reading *bread* as “breed”) were excluded from the analysis.

The results are outlined in Table 2. All three LPDs made more migration errors than controls (LM $t = 21.95$, $p < 0.001$ one-tailed; E: $t = 9.49$; $p < 0.001$ one-tailed; LL $t = 4.81$, $p < 0.01$ one-tailed). Because there was no variance in the number of substitution errors made by controls, a Fisher’s exact test was used (instead of Crawford’s t-tests) to compare LPDs’ performance to their respective control groups. All three LPDs made as many substitution errors as controls, all $ps > 0.50$ one-tailed. Both LM and EL made as many N errors as controls, both $t = 1.11$, $p = 0.16$ one-tailed. Because there was no variance in the number of N errors made by LL’s control group, a Fisher’s exact test was used instead of Crawford’s t-test, which indicated that she made as many N errors on the task as controls, $Z = 0.71$, $p = 0.24$ one-tailed.

The finding that LM, EL and LL’s reading errors were selective to the migration of letters within words suggests that their LPD cannot be attributed to lexical guessing.

Table 2. Percentage of errors on reading aloud words in the migration and substitution conditions.

	LM	EL	LM and EL controls	LL	LL controls
Migration errors	27.59***	15.52***	6.32 (0.89)	12.07**	2.07 (1.89)
Substitution errors	3.33	0.00	0.00 (0.00)	0.00	0.00 (0.00)
N errors	2.27	2.27	0.95 (1.12)	2.27	0.00 (0.00)

Note: Numbers in parentheses denote standard deviation of the mean for control groups

** $p < 0.01$, *** $p < 0.001$ compared to control group.

Visual lexical decision. A visual lexical decision task was also administered to determine whether migration errors made by LPDs were the result of lexical guessing. Forty non-migratable words formed the word condition in this task. Three nonword conditions were created by modifying the word items – a migratable nonword condition (*coisun* (derived from cousin), $N = 16$), a single-substitution nonword condition (*eamly* (derived from early), $N = 12$), and a double-substitution nonword condition (*provare* (derived from private), $N = 12$). Single and double substitution items were included because both have previously been used in research as a comparison condition for migratable items (e.g. Beyersmann, Castles, & Coltheart, 2001; Beyersmann, Coltheart, & Castles, 2012; Beyersmann, Duñabeitia, Carreiras, Coltheart, & Castles, 2013; Perea & Lupker, 2004; Perea & Fraga, 2006).

Items in the migratable nonword condition were matched as closely as possible to items in the single- and double-substitution condition on bigram frequency (migration condition $M = 719.04$, $SD = 415.91$; single-substitution condition $M = 578.54$, $SD = 336.08$; double-substitution condition $M = 713.68$, $SD = 553.36$), and the written frequency of the words that they were derived from (migration condition $M = 87.56$, $SD = 125.20$; single-substitution condition $M = 96.89$, $SD = 116.29$; double-substitution condition $M =$

72.64, $SD = 112.39$). Words and nonwords were intermixed with 112 additional items, which were not used to address the research questions in the present study. Items were presented over two separate tasks, such that a nonword and the word it was derived from were not presented in the same task.

So that we could be relatively certain that a ‘word’ response to a nonword was due to the participant misreading the nonword as the word it was derived from, nonwords in the migration condition and the double-substitution condition did not have a single substitution neighbour. Furthermore, the nonwords in the single substitution condition did not have a single substitution neighbour other than the word that they were derived from. To further ensure that participants’ ‘word’ responses were due to their misreading of the nonword as its word partner, we removed nonwords derived from words that participants did not know. We determined whether or not a participant knew a word based on their performance on the ‘word’ condition of the visual lexical decision task, and their reading aloud of these words. If a participant could not read aloud the word and did not recognize the word in the visual lexical decision task, the word was defined as unknown, and hence its nonword counterpart was removed from their individual analysis. This comprised 5.00% of LM’s data, 2.50% of EL’s data, and 2.92% ($SD = 3.68\%$) of their control group’s data. For LL, 2.50% of her data was removed, and 1.00% ($SD = 2.24\%$) of her control group’s data was removed.

The results are outlined in Table 3. All three LPDs accepted more migratable nonwords as words than controls (LM $t = 3.59$, $p = 0.01$ one-tailed; EL $t = 2.59$, $p = 0.02$ one-tailed; LL $t = 2.89$, $p = 0.02$ one-tailed). Both EL and LL accepted as many single- and double-substitution nonwords as words as controls, both $t < 1.12$, $p > 0.16$ one-tailed. LM, however, accepted more single- and double-substitution nonwords as words than controls (single-substitution $t = 2.51$, $p = 0.03$ one-tailed; double-substitution $t = 4.54$, $p = 0.003$ one-tailed).

The finding that EL and LL's excessive errors on the visual lexical decision task were selective to the migration condition suggests that their migration errors are not the result of lexical guessing. In contrast, LM's excessive errors on the task were not selective to the migration condition – she also made more substitution errors on the task than controls. This finding suggests that a lexical guessing strategy may have been the cause of LM's migration errors on the visual lexical decision task.

Table 3. Percentage of migration errors, single-substitution (sub) errors and double-substitution (sub) errors on the visual lexical decision task.

	LM	EL	LM and EL controls	LL	LL controls
Migration errors	64.29*	53.33*	24.89 (10.16)	43.75*	12.58 (9.82)
Single-sub errors	33.33*	8.33	6.94 (9.74)	8.33	3.33 (4.56)
Double-sub errors	25.00**	8.33	2.90 (4.51)	0.00	3.33 (7.45)

Note: Numbers in parentheses denote standard deviation of the mean for control groups

* $p < 0.05$, ** $p < 0.01$ compared to control group.

Assessing the Orthographic-Visual Analysis Stage of Reading

To investigate whether LPD is caused by an orthographic-visual analysis deficit, we administered a sequential same-different decision task and a reading aloud nonwords task. If LPD is caused by an orthographic-visual analysis deficit, LPDs should make more migration errors than controls on tasks that tap prelexical processing (e.g., same-different decision) since orthographic-visual analysis is a prelexical process. Furthermore, if their migration errors are caused by an orthographic-visual analysis deficit, LPDs should make more migration errors than controls during lexical and nonlexical reading.

Sequential same-different decision. The sequential same-different decision task consisted of 139 word pairs and 139 consonant-string pairs⁶, which were four or five letters in length. Half of the items were the same (e.g., *beard-beard*; *bfgsk-bfgsk*), and half were different (*beard-bread*; *bfgsk-bfsgk*). Half of the items in the different condition were different via the transposition of internal letters (e.g., *trial-trail*), and half were different via the substitution of a single letter (e.g., *chuck-check*). Items were included in both the same and the different condition (i.e., participants made responses to both *trial-trail* and *trial-trial*). Six versions of the task were created and presented over two sessions, such that participants only saw one version of the item (either in the same or in the different condition) in a single session. These 280 items were intermixed with an additional 280 items (half same, half different), which were not used to address the research questions in the present study.

Same-different decision trials were presented using DMDX software (Forster and Forster, 2003). A schematic of a single trial is outlined in Figure 2. The first item was both backwards masked and presented in a different case to the second item to ensure that participants could not match the items based on low-level perceptual overlap. Participants were instructed to press a button with their right hand if they thought the two items were the same, and to press a button with their left hand if they thought the two items were different. Participants were given 8 practice trials before commencing the task. No performance-based feedback was given to participants at any stage during the task

⁶ The task was designed to have 140 word pairs and 140 consonant-string pairs. However, one word pair in the same migration condition (e.g., *slime-slime*) and one consonant-string pair in the different migration condition (e.g., *dktlp-dltkp*) were removed from the analysis as they were not presented correctly.

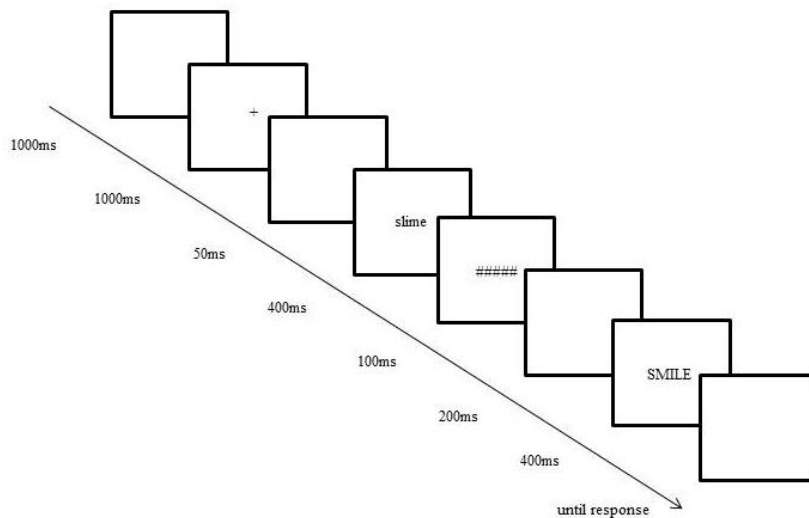


Figure 2. Schematic of a single same-different decision trial.

As LPDs have been found to have intact letter identification skills (Friedmann & Rahamim, 2007; Kohnen et al. 2012), the substitution condition was used as an indication of baseline performance on the task. If LPD is due to an orthographic-visual analysis deficit, LPDs should be poorer than controls at detecting a difference between two migratable items (e.g., *slime-smile*), relative to the baseline condition (e.g., *tiger-timer*).

Table 4 displays participants' accuracy on the different condition (that is, their ability to detect that two items are different). Participants' d' scores based on their hits (correctly responding "different" to two different items e.g., *slime-smile*) and false alarms (incorrectly responding "different" to two same items e.g., *slime-slime*) on the migration and substitution condition are also included in Table 4.

All statistical analyses for the task were based on participants' accuracy on the different migration condition relative to their accuracy on the different substitution condition, using the Revised Standardised Difference Test (RSDT: Crawford & Garthwaite, 2005). All three LPDs were significantly poorer than controls at detecting that

two migratable words were different relative to the substitution condition, however this only reached significance for EL and LL (EL $t = 4.68$, $p = 0.003$ one-tailed; LL $t = 2.82$, $p = 0.02$ one-tailed; LM $t = 1.74$, $p = 0.07$). All three LPDs were not significantly poorer than controls at detecting that two migratable consonant strings were different, relative to the substitution condition, all $t < 1.10$, $p > 0.16$.

Table 4. Percentage accuracy for the different migration (mig) and substitution (sub) conditions on the same-different decision task, and d' scores.

		LM		EL		LM and EL controls		LL		LL controls	
		Accuracy	d'	Accuracy	d'	Accuracy	d'	Accuracy	d'	Accuracy	d'
Words	Mig	40.00	1.22	54.29	1.00	89.52 (6.68)	3.03 (0.68)	71.43	1.83	94.29 (5.35)	3.69 (0.59)
	Sub	80.00	3.01	100.00	3.35	93.81 (2.81)	3.25 (0.45)	91.43	2.60	96.00 (8.94)	3.85 (0.99)
Consonants	Mig	41.18	1.08	67.65	0.34	65.69 (8.86)	0.73 (0.53)	85.29	0.61	74.71 (25.01)	1.66 (1.08)
	Sub	22.86	0.43	80.00	0.78	60.00 (15.65)	1.16 (0.45)	65.71	0.29	73.71 (15.31)	1.68 (0.78)
Nonwords	Mig	58.33	1.67	54.17	0.96	88.54 (9.85)	3.24 (0.77)	66.67	1.35	88.33 (11.56)	2.83 (0.99)
	Sub	70.83	1.99	100.00	2.92	96.88 (6.25)	3.85 (0.78)	87.50	2.02	95.83 (5.10)	3.22 (0.75)

Note: Numbers in parentheses denote the standard deviation of the mean for control groups

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The finding that all three LPDs were no poorer than controls at detecting a difference between two migratable consonant-strings seems inconsistent with an orthographic-visual analysis deficit account of LPD. If LPD is caused by an orthographic-visual analysis deficit, then LM, EL and LL should be poorer than controls at detecting a difference between two migratable items, regardless of their lexicality.

However, this result may have been due to participants not having enough time to process the entire consonant-string. Letters in words are thought to be processed in parallel as a single unit of information. In contrast, there is no higher-order representation for consonant strings, and therefore each letter needs to be processed serially as its own unit of information. The limited stimulus presentation time in the task (400ms) may have therefore meant that children only had enough time to process the beginning letters of the items in the consonant-string condition. If only the beginning letters are processed, then a correct response to many of the items in the different migration condition would require intact letter identification skills, but not necessarily intact letter position coding skills. For example, if participants are presented with the consonant-string pair *stlkd-skltd*, but they only have enough time to process the first three letters of the consonant string, *stl-skl*, participants need only detect that the letter identities *t* and *k* are different from one another to make a correct response. If participants were only processing the beginning letters of the consonant-string pairs, then the finding that LPDs did not make more errors on the migration condition is not surprising, as LPDs have been found to have intact letter identification abilities (Friedmann & Rahamim, 2007; Kohnen et al., 2012).

One way to investigate whether or not participants had enough time to process all letters in the consonant-string condition is to see whether there is a position effect. If participants did not have enough time to process the entire consonant-string, we should find that they are better at detecting a difference between two consonant strings if the letters are different at the beginning of the pair, than if the letters are different at the end of

the pair.

In a post-hoc analysis, we explored whether there was merit in this alternative hypothesis. Items that differed via the substitution of a single letter in the first internal position of the word (e.g., *nkdcg-njdcg*) were classified as having a ‘beginning difference’, and items that differed via the substitution of a single letter in the final internal position of the word (e.g., *fkmzd-fkmtd*) were classified as having an ‘end difference’. The substitution condition rather than the migration condition was used because many of the different migratable items had both a beginning and end difference (e.g., *xtkjd-xtktd*).

All participants were combined to form one group for this item analysis. We used a Wilcoxon matched pairs test to compare the proportion correct on the two groups of items. Participants identified significantly more beginning differences (74.60%) in the consonant-string condition than end differences (58.574%; $Z = 2.51$, $p = 0.006$ one-tailed). In contrast, participants identified as many beginning differences (93.57%) in the word condition as end differences (94.76%; $Z = 0.51$, $p = 0.304$ one-tailed).

Following this finding, we decided to administer a same-different decision task with orthographically legal nonwords (e.g., *scirm-scrim*). While the letters in legal nonwords are not thought to be processed in parallel like words, the letters can be mapped onto a higher-order representation. For example, the consecutive letters *i* and *r* in the nonword *scirm* can be mapped onto the digraph *ir*. That is, the letters in legal nonwords can be ‘chunked’ (*s*, *c*, *ir* and *m*) and, for this reason, are likely to be processed faster than consonant-strings which cannot be chunked.

The nonword same-different decision task consisted of 96 nonword pairs. Forty-eight of the pairs were in the same condition, and 48 were in the different condition. Half of the items in the different condition were different via the transposition of two internal letters (e.g., *scirm-scrim*), and half were different via the substitution of a single letter (e.g., *froy-floy*). The same condition consisted of 48 nonword pairs. In contrast to the word and

consonant string same-different decision task, nonwords in the same condition were a new set of items, not derived from the items in the different condition (i.e., participants did not see *scirm-scrim* and *scirm-scirm*). Nonwords were presented to participants during a single task, and under the same presentation conditions as described for the words and consonant-strings task.

By the time we assessed LM and EL on this task they were in the second semester of grade 5. Therefore, we compared their performance on this task to a new control group of 4 children in their second semester of grade 5.

Table 4 displays participants' accuracy on the different conditions. Participants' d' scores based on their hits (correctly responding "different" to two different items e.g., *scirm-scirm*) and false alarms (incorrectly responding "different" to two same items e.g., *garp-garp*) on each condition are also included in Table 4. False alarms were calculated from participants' performance on all 48 items in the same condition.

EL was significantly poorer than controls at detecting when two migratable nonwords were different relative to the substitution condition, EL $t = 4.47$, $p = 0.01$ one-tailed. LM and LL, however, did not show this effect, both $t < 1.64$, $p > 0.10$. We assessed for a position effect in the same way as we did for the consonant-string and word items. Participants correctly identified as many beginning differences (95.14%) as end differences (91.67%; $Z = 0.54$, $p = 0.30$ one-tailed), indicating that they had enough time to process the entire letter string.

The finding that all three LPDs made more word migration errors than controls on a sequential same-different decision task is consistent with an orthographic-visual analysis deficit account of LPD, as is the finding that EL made more nonword migration errors on the task. The finding that LM and LL did not make more nonword migration errors on the sequential same-different decision task is, however, inconsistent with an orthographic-visual analysis deficit, and will be followed up in the discussion.

Reading aloud nonwords. Nonwords were created from 25 nonword pairs which were migratable via the transposition of two internal adjacent letters (e.g., *torm-trom*). Pairs were selected to have a significant difference in bigram frequency between the two nonwords (lower bigram frequency counterpart $M = 789.56$, $SD = 594.36$; higher bigram frequency counterpart $M = 1389.80$, $SD = 841.41$). Nonwords were selected to match their migration partner as closely as possible on substitution N (lower bigram frequency counterpart $M = 2.44$, $SD = 2.38$; higher bigram frequency counterpart $M = 3.00$, $SD = 2.65$). Nonwords were randomized and intermixed with 25 additional monosyllabic nonwords that were not used to answer the research questions in this paper. Three versions of the task were created such that participants did not see a nonword and its migration partner in the same task. Participants were told that all items were nonwords before commencing the task.

The results from the nonword reading task are presented in Table 5. Both LM and LL made significantly more nonword migration errors on the task than controls (LM $t = 6.46$, $p < 0.001$ one-tailed; LL $t = 2.96$, $p = 0.02$ one-tailed) and made as many non-migration related errors as controls (LM $t = 0.04$, $p = 0.48$ one-tailed; LL $t = 1.82$, $p = 0.07$ one-tailed). EL did not make more nonword migration errors than controls, $t = 0.18$, $p = 0.43$ one-tailed, and made more non-migration related errors than controls, $t = 2.95$, $p = 0.02$ one-tailed.

Table 5. Percentage of migration errors (mig error) and non-migration related errors (non-mig error) on reading aloud nonwords.

	LM	EL	LM and EL controls	LL	LL controls
Mig error	40***	6	5.00 (5.02)	16*	4.40 (3.58)
Non-mig error	12	36*	12.33 (7.42)	20	7.20 (6.42)

Note: Numbers in parentheses denote standard deviation of the mean for control groups

* $p < 0.05$, *** $p < 0.001$ compared to control group.

Following the finding that EL showed the opposite effect to that displayed by LM and LL (i.e., as many migration errors as controls, but more non-migration related errors than controls), we decided to inspect EL's nonword reading data more closely. We found that 23% of ELs non-migration errors were what we have termed, 'over-sequential' errors. An 'over-sequential' error was defined as an error that appeared likely to have occurred as a result of sounding out each letter in the nonword in isolation, and then blending these sounds together to form a spoken response. For example, EL read *kerm* as /k /ε/ /r/ /m/. That is, instead of reading the letters *e* and *r* together to correctly form the sound /æɾ/, he sounded out these two letters separately. For two of these errors, EL first misread the nonword as its migration partner, and then self-corrected with an over-sequential error. Furthermore, for all but one of EL's over-sequential errors, EL demonstrated that he knew the sound associated with the multi-letter grapheme he over-sequentialised by correctly producing it on at least two other items within the list. EL's control group did not make a single 'over-sequential' error on this task. This finding suggests that EL's limited migration errors on this task (compared to the other LPDs in the study) may have been the result of him sounding out each letter in isolation of the other letters within the word.

The findings from the reading aloud nonwords task suggest that LPD is most likely caused by an orthographic-visual analysis deficit. However, there appears to be variation in task performance amongst the three LPDs in the present study.

Item variables influencing nonword migration errors. In the present study we also explored the possibility that there may be specific item variables that influence whether or not LPDs will make nonword migration errors. Specifically, we explored whether the bigram frequency of the nonword migration counterpart relative to the bigram frequency of the nonword itself, influenced whether or not a nonword migration error would be made.

We investigated the influence of bigram frequency on nonword reading by

analysing the migration errors made by LM and LL. Specifically, we compared the number of migration errors made on the lower bigram frequency partner ($N = 25$) to the number of migration errors made on the higher bigram frequency partner ($N = 25$). The other participants' results (EL and both control groups) were not investigated in this additional analysis as they made very few migration errors on the task. Both LM and LL read as many nonwords as their higher bigram frequency migration partner (LM = 40%, LL = 8%) as they did nonwords as their lower bigram frequency partner (LM = 40%; LL = 24%; both Fisher's exact $p > 0.12$ one-tailed).

While bigram frequency was not found to mediate migration errors on this task, a post-hoc analysis revealed that LM and LL's migration errors were influenced by the complexity of the graphemes that made up each nonword. LM and LL were more likely to migrate a two-letter grapheme into two single-letter graphemes (e.g., reading *kerm* as "krem") than to migrate two single-letter graphemes into a two-letter grapheme (e.g., reading *krem* as "kerm"). Both LM and LL were found to migrate significantly more two-letter graphemes into single letter graphemes (LM = 66.67%, LL = 33.33%) than two single-letter graphemes into a two letter grapheme (LM = 11.11%, LL = 0%, both Fisher's exact $p < 0.02$ two-tailed).

An examination of the order of item presentation was conducted to investigate whether the errors where a two-letter grapheme migrated into two single-letter graphemes were due to participants being primed by the two single-letter graphemes. That is, we examined whether participants saw the two single letter graphemes (e.g., *fremp*) prior to making an error where they migrated a two-letter grapheme into these two-single letters (e.g., reading *kerm* as "krem"). Of the 18 errors made by LM and LL where a two-letter grapheme was migrated into two single letters (e.g., where *kerm* was read as "krem"), only three errors were made directly after having seen a nonword that comprised the same two single letters (e.g., *fremp*).

Discussion

This study investigated the locus of impairment in three English-speaking children with developmental LPD. Previous research has used a cognitive model of reading aloud to identify three alternative processing components that may be the cause of LPD: the phonological output buffer, the orthographic input lexicon, and orthographic-visual analysis. First, we aimed to replicate previous findings that have ruled out a phonological output buffer deficit and an orthographic input lexicon deficit account of LPD. We then went on to extend previous findings that suggest LPD is caused by an orthographic-visual analysis deficit.

Assessing the Phonological Output Buffer

It is plausible to assume that the excessive migration errors made by LPDs are due to the phonemes in the phonological output buffer being swapped around before the word is pronounced. Together with previous studies, our findings strongly refute this hypothesis (Friedmann & Rahamim, 2007; Kohnen et al., 2012; see also Collis, Kohnen, & Kinoshita, 2013). All three LPDs in the present study were either within or above the average range on various standardized tests that draw heavily on a functioning phonological output buffer to be completed successfully. Furthermore, LPDs were asked to repeat a subset of the migratable words that they had previously made a migration error on in a reading aloud task. Each LPD performed this task without making a single migration error, indicating that their reading aloud errors were not caused by an inability to produce the word's phonemes in the correct order.

In recent years, various researchers have suggested that underlying dyslexia is a phonological processing deficit (Ramus, 2003; Snowling, 1998; Snowling, 2001; Stanovich, 1988). The findings from the present study indicate that, while some children with reading difficulties have phonological processing difficulties, other children's reading difficulties are likely to reflect an alternative processing deficit. For example, surface

dyslexia is most likely caused by an orthographic processing deficit (e.g., Broom & Doctor, 1995; Castles & Coltheart, 1993, 1996; Temple, 1997), attentional dyslexia is most likely caused by a letter-to-word binding deficit (Friedmann, Kerbel and Shvimer, 2010; Rayner, Murphy, Henderson, & Pollatsek, 1989), and LPD is most likely caused by a letter position coding deficit (for more discussion of heterogeneity within developmental dyslexia, see Castles, McLean, & McArthur, 2010; McArthur et al., 2013; Zoccolotti & Friedman, 2010).

Assessing the Orthographic Input Lexicon

It is also plausible to assume that the migration errors made by LM, EL and LL are the result of lexical guessing due to an impoverished orthographic input lexicon. The finding that all three LPDs read aloud nonmigratable irregular words as well as controls indicates that this is not the case. Furthermore, EL and LL made more migration errors than controls during a reading aloud task and a visual lexical decision task but did not make more substitution and N errors than controls. These findings indicate that EL and LL's errors on these tasks were specific to the migration of letters within the word and were therefore not due to lexical guessing.

In contrast to EL and LL, LM made more migration errors than controls on the visual lexical decision task *and* more substitution errors on the task. This finding suggests that perhaps LM's tendency to make excessive migration errors is the result of lexical guessing. While this finding does not fall in line with our predictions, we believe that LM's lexical guessing was confined to this task, and that her broader tendency to make more migration errors than her peers cannot be attributed to a lexical guessing strategy. If LM's excessive migration errors are the result of lexical guessing, then she should have been found to make more errors that are visually similar to the target word when reading aloud (e.g., reading *slime* as "slide" or "slim") than controls. This was not the case. Like EL and LL, LM made more migration errors than controls when reading aloud, but the same

amount of substitution and N errors.

Assessing the Orthographic-Visual Analysis Stage of Reading

The first aim of the present study was to replicate the finding that LPD cannot be attributed to a phonological output buffer deficit or an orthographic input lexicon deficit. Our findings converge with previous research that has ruled out these two possible loci as the source of migration errors seen in LPD (Friedmann & Rahmim, 2007; Kohnen et al., 2012). Having addressed our first aim, we now turn to a discussion of our second aim: to extend the investigation of a possible orthographic-visual analysis deficit account of LPD.

The present study extended Kohnen et al.'s (2012) study in three ways: (1) administering a sequential same-different decision task, (2) administering consonant-strings and orthographically legal nonwords in the sequential same-different decision task, and (3) manipulating bigram frequency in a nonword reading task. We hoped that making these changes would provide us with tasks that were more sensitive to an orthographic-visual analysis deficit, and hence enable us to draw stronger conclusions regarding the locus of impairment in English LPD.

In the present study we administered a sequential same-different decision task to ensure that participants would be unable to adopt a strategy whereby they compare each letter in the pair to one another. We found that EL and LL made significantly more word migration errors on the task than controls. LM also showed this trend, however it did not reach significance. One key difference between the present study and Kohnen et al.'s (2012) study was EL's performance on the same-different decision task. While EL did not make more migration errors on Kohnen et al.'s simultaneous same-different decision task (where the items were displayed side by side), he made significantly more migration errors on a sequential variant of the task in the present study. One interpretation of this finding is that EL was adopting a letter-by-letter matching strategy during Kohnen et al.'s (2012) simultaneous same-different decision task. When he was unable to adopt this strategy

during the present study, due to the sequential presentation of words, he made significantly more migration errors than controls.

An alternative interpretation of EL's excessive migration errors on the same-different decision task in the present study is that a sequential variant of the task encourages participants to convert the word into a phonological form due to the limited presentation time of the items. It might therefore be that EL made excessive migration errors on the sequential task because he compared the words in each pair based on phonological form, whereas in Kohnen et al's (2012) simultaneous task, words were compared based on their orthographic form. We believe this alternative hypothesis to be unlikely for two reasons. Firstly, a wealth of research has shown that responses made on a same-different decision task are based on prelexical orthographic representations rather than phonological representations (see Besner et al., 1984, Kinoshita & Norris, 2009). Secondly, EL was found to be within (or above) the average range on tests that assess phonological processing. It is therefore highly unlikely that EL's excessive migration errors on the sequential same-different decision task could be reflecting a difficulty in comparing phonological forms.

A consonant-string condition in the same-different decision task was included in the present study under the assumption that a letter position coding deficit should manifest itself in responses to all letter-strings, regardless of lexicality. Contrary to our prediction, LPDs did not make more migration errors than controls on the consonant-string condition. We believe that this finding was due to the different mechanisms underlying the processing of letters in words and in consonant-strings. While letters in words are thought to be processed in parallel as a single unit, each letter in a consonant-string needs to be processed serially as a single unit. This means that letters in consonant-strings are likely to take longer to process than letters in words. The post-hoc finding that participants were significantly better at identifying a difference between two consonant strings when the

difference occurred towards the beginning of the consonant pair (*fktzm-fltzm*) than when the difference occurred towards the end of the consonant pair (*fktzm-fkltm*) suggests that 400ms was not enough time for participants to process the entire consonant-string. For this reason, we believe that participants' performance on the consonant-string condition cannot be taken as evidence either for or against an orthographic-visual analysis deficit account of LPD.

Following this finding, we conducted a sequential same-different decision task with orthographically legal nonwords. We found that while EL made significantly more migration errors than controls on this task, LM and LL did not. The finding that EL made more word *and* nonword migration errors on a same-different decision task strongly suggests that EL's excessive migration errors are caused by an orthographic-visual analysis deficit. In contrast, the finding that LM and LL made more migration errors on the word condition, but not on the nonword condition is not predicted by an orthographic-visual analysis deficit account of LPD. Rather, LM and LL should have been found to make more migration errors on a sequential same-different decision task, regardless of the lexicality of the items. However, LM and LL's data are still most consistent overall with an orthographic-visual analysis deficit. Further investigations may need to focus on the interaction between lexicality effects and orthographic-visual analysis deficits in LPD.

We also administered a nonword reading task in the present study. If LPD is caused by an orthographic-visual analysis deficit, we should find that LPDs not only make more word migration errors (e.g., reading *slime* as "smile") than controls, but also more nonword migration errors (e.g., reading *pilf* as "plif"), as a deficit at the orthographic-visual analysis stage of reading should impede both lexical and nonlexical reading. In the present study, we found that LM and LL made more nonword migration errors (e.g., reading *pilf* as "plif") than controls. This finding is in contrast with Kohnen et al's (2012) finding that all three LPDs made as many nonword migration errors as controls. Interestingly, the one

LPD in the present study who did not make excessive nonword migration errors (EL) was one of the three LPDs in Kohnen et al's (2012) study who did not make excessive nonword migration errors when reading aloud. This finding is consistent with research in Hebrew that has found that while some LPDs make nonword migration errors, others do not (Friedmann & Rahamim, 2007). EL's over-sequential errors in the present study – where each letter was sounded out in isolation and then blended together to form a response – suggest that individual differences in strategy use might be one predictor of whether or not LPDs will make nonword migration errors.

Contrary to our exploratory hypothesis, we found nonword bigram frequency to have no influence over whether or not a migration error was made. That is, LM and LL were no more likely to read a nonword as its higher bigram frequency partner than they were to read a nonword as its lower bigram frequency partner. The majority of migration errors made by LPDs occur when two adjacent letters in the middle of a word can migrate to form a new word. Considering it is the internal letters of the nonword that are most prone to migration, it is perhaps not surprising that the bigram frequency of the entire letter-string (external letters included) did not influence whether or not a migration error was made. Instead, it may be other factors specific to the letters that are most susceptible to migration that influence whether or not a migration error will be made.

This suggestion was supported by the post-hoc finding that the complexity of the nonword's internal grapheme influenced whether or not a migration error was made. We found that LM and LL were more likely to swap the letters in a two-letter grapheme around to form two single-letter graphemes, than to swap two single letters around to form a two-letter grapheme (i.e., *kerm* was read as “krem” more than *krem* read as “kerm”)⁷.

⁷ Note that following this finding we also analysed the influence of internal bigram frequency on migration errors using Solso and Juel's (1980) bigram frequency count database. That is, we analysed whether or not LM and LL were more likely to migrate the lower frequency bigram *li* in the nonword *plim* into the higher frequency bigram *il* (resulting in the misreading of the nonword as “pilm”). We found no influence of internal bigram frequency on LM and LL's migration errors.

One plausible explanation for this finding is that children are likely to be introduced to the sounds that the letters of the alphabet make (single-letter graphemes) before they are introduced to the sounds that two letters of the alphabet make together (two-letter graphemes). What this finding might therefore reflect is an age of acquisition effect. When the nonlexical route is provided with ambiguous letter position information, the default may be to resort to the letter-sounds that were first learnt. Future studies may seek to further our post-hoc finding by directly testing the hypothesis that some graphemes may be more susceptible to migration than others.

Conclusion

The aim of this multiple single-case study was to both replicate and extend previous findings regarding the locus of impairment in English LPD. Our findings converge with previous research by strongly suggesting that LPD cannot be attributed to a phonological output buffer or orthographic input lexicon deficit. Rather, our results suggest that LPD is most likely caused by a deficit specific to the coding of letter position at the orthographic-visual analysis stage of reading.

In line with previous studies, however, there was some variability in performance amongst the three children on the tasks designed to explicitly assess for an orthographic-visual analysis deficit. One thing that is becoming increasingly clear as research on LPD progresses is that localizing the source of the migration errors seen in LPD is no easy feat. While identifying what *does not cause* migration errors (i.e., a phonological output or orthographic input lexicon deficit) is relatively straight forward, identifying what *causes* migration errors is not as clear-cut. The findings from the present study suggest that variations in the manifestation of an orthographic-visual analysis deficit may be, at least in part, due to individual differences in strategy use. Therefore, in order to maximize the potential of localizing the deficit underpinning LPD, future research must ensure that the tasks used either eliminate or greatly reduce the opportunity for compensatory strategies to

be adopted.

Finally, the finding that the three children in the present study were found to have great difficulty in reading migratable words, in the absence of any other obvious reading or spoken language difficulty, attests to the heterogeneity of dyslexia and its underlying causes. Our findings strongly suggest that not all children with reading difficulties have an impairment in phonological processing. Rather, our findings join a growing body of research in advocating the need to map this heterogeneity in developmental dyslexia, and to develop diagnostic tools that assess the variety of its underlying causes.

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References

- Baayen, R. H., Piepenbrock, R., & Gulikers, L. (1995). *The CELEX Lexical Database (CD-ROM)*. University of Pennsylvania, Philadelphia, PA: Linguistic Data Consortium.
- Besner, D., Coltheart, M., & Davelaar, E. (1984). Basic processes in reading: Computation of abstract letter identities. *Canadian Journal of Psychology* 38(1), 126-134. doi: 10.1037/h0080785
- Beyersmann, A. E., Castles, A., & Coltheart, M. (2011). Early morphological decomposition during visual word recognition: Evidence from masked transposed-letter priming. *Psychonomic Bulletin and Review*, 18(5), 937-942. doi: 10.3758/s13423-011-0120-y
- Beyersmann, A. E., Coltheart, M., & Castles, A. (2012). Parallel processing of whole-words and morphemes in visual word recognition. *The Quarterly Journal of Experimental Psychology*, 65(9), 1306-1326. doi: 10.1080/17470218.2012.672437
- Beyersmann, A. E., Duñabeitia, J. A., Carreiras, M., Coltheart, M., & Castles A. (2013). Early morphological decomposition of suffixed words: Masked priming evidence with transposed-letter nonword primes. *Applied Psycholinguistics*, 34(5), 869-892. doi: <http://dx.doi.org/10.1017/S0142716412000057>
- Broom, Y. M., & Doctor, E. A. (1995). Developmental surface dyslexia: A case study of the efficacy of a remediation programme. *Cognitive Neuropsychology*, 12(1), 69-110. doi: 10.1080/02643299508251992
- Castles, A., and Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition*, 47(2), 149-180. doi: 10.1016/0010-0277(93)90003-E
- Castles, A., & Coltheart, M. (1996). Cognitive correlates of developmental surface dyslexia: A single case study. *Cognitive Neuropsychology*, 13(1), 25-50. doi: 10.1080/026432996382051

- 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
- Castles, A., Coltheart, M., Wilson, K., Valpied J., & Wedgwood J. (2009). The genesis of reading ability: What helps children learn letter-sound correspondences? *Journal of Experimental Child Psychology*, 104(1), 68-88. doi: 10.1016/j.jecp.2008.12.003
- Castles, A., McLean, G.M.T., & McArthur, G. (2010). Dyslexia (neuropsychological). *Wiley Interdisciplinary Reviews: Cognitive Science (WIREs)*, 1(3), 426-432. doi: 10.1002/wcs.16
- Collis, N.L., Kohnen, S., & Kinoshita, S. (2013). The role of visual spatial attention in adult developmental dyslexia. *Quarterly Journal of Experimental Psychology*, 66(2), 245-260. doi: 10.1080/17470218.2012.705305
- 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. (2005). Evaluation of criteria for classical dissociations in single-case studies by Monte Carlo simulation. *Neuropsychology*, 19(5), 664-678. doi: 10.1037/0894-4105.19.5.664
- 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
- Davis, C. J. (2005). N-Watch: A program for deriving neighbourhood size and other psycholinguistics statistics. *Behaviour Research Methods*, 37(1), 65-70. doi: 10.3758/BF03206399

- Denckla, M. B., & Rudel, R. G. (1976). Rapid 'automatized' naming (R.A.N): Dyslexia differentiated from other learning disabilities. *Neuropsychologia*, 14(4), 471-479. doi: 10.1016/0028-3932(76)90075-0
- Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers*, 35(1), 116-124.
- Friedmann, N., Dotan, D., Rahamim, E. (2010a). Is the visual analyzer orthographic-specific? Reading words and numbers in letter position dyslexia. *Cortex*, 46(8), 982-1004. doi: 10.1016/j.cortex.2009.08.007
- Friedmann, N., Kerbel, N., & Shvimer, L. (2010). Developmental attentional dyslexia. *Cortex*, 46(10), 1216-1237. doi: 10.1016/j.cortex.2010.06.012
- Friedmann, N., & Gvion, A. (2001). Letter position dyslexia. *Cognitive Neuropsychology*, 18(8), 673-696. doi: 10.1080/02643290143000051
- Friedmann, N., and Haddad-Hanna, M. (2012). Letter position dyslexia in Arabic: From form to position. *Behavioural Neuropsychology* 25, 193-203, doi: 10.3233/BEN-2012-119004. doi:10.3233/BEN-2012-119004
- Friedmann, N., and Rahamim, E. (2007). Developmental letter position dyslexia. *Journal of Neuropsychology* 1, 201-236. doi: 10.1348/174866407X204227
- Høien, T., Lundberg, I., Larsen, J. P., & Tønnessen, F. E. (1989). Profiles of reading related skills in dyslexic families. *Reading and Writing*, 1(4), 381-392. doi: 10.1007/BF00386268
- Kinoshita, S., & Norris, D. (2009). Transposed-letter priming of prelexical orthographic representations. *Journal of Experimental Psychology: Learning*, 35(1), 1-18. doi: 10.1037/a0014277.
- Kohnen, S., & Castles, A. (2013). Pirates at parties: Letter position processing in developing readers. *Journal of Experimental Child Psychology*, 50(14), 3681-3692.

doi: <http://dx.doi.org/10.1016/j.jecp.2012.08.011>

- Kohnen, S., Marinus, E., Friedmann, N., Anandakumar, T., Castles, A., Nickels, L., & McArthur, G. (2014). *The Letter Position Test (LetPos)*, www.motif.org.au.
- Kohnen, S., Nickels, L., Castles, A., Friedmann, N., McArthur, G. (2012). When ‘slime’ becomes ‘smile’: developmental letter position dyslexia in English. *Neuropsychologia*, 50(14), 3681-3692. doi: 10.1016/j.neuropsychologia.2012.07.016
- Korkman, M., Kirk, U., & Kemp, S. (1998). *A developmental neuropsychological assessment (NEPSY)*. Texas, USA: The Psychological Corporation.
- Mann, V. A., Liberman, I. Y., & Shankweiler, D. (1980). Children’s memory for sentences and word strings in relation to reading ability. *Memory and Cognitive*, 8(4), 329-335. doi: 10.3758/BF03198272
- Mann, V. A., & Liberman, I. Y. (1984). Phonological awareness and verbal short-term memory. *Journal of Learning Disabilities*, 17(1), 592-599, doi: 10.1177/002221948401701005
- McArthur G., Eve P.M., Jones K., Banales E., Kohnen S., Anandakumar T., Larsen L., Marinus E., Wang H., & Castles A. (2012). Phonics training for English speaking poor readers. *Cochrane Database of Systematic Reviews*, 12, 1-104. doi: 10.1002/14651858.CD009115.pub2
- McArthur, G., Kohnen, S., Larsen, L., Jones, K., Anandakumar, T., Banales, E., & Castles, A. (2013). Getting to grips with the heterogeneity of developmental dyslexia. *Cognitive Neuropsychology*, 30(1), 1-24. doi: 10.1080/02643294.2013.784192
- Perea, M., & Fraga, I. (2006). Transposed-letter and laterality effects in lexical decision. *Brain and Language*, 97(1), 102-109. doi: 10.1016/j.bandl.2005.08.004
- 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. doi:10.1016/j.jml.2004.05.005
- Ramus, F. (2003). Developmental dyslexia: specific phonological deficit or general sensorimotor dysfunction? *Current Opinion in Neurobiology*, 13(2), 212-218. doi:10.1016/S0959-4388(03)00035-7
- Rastle, K., & Coltheart, M. (1998). Whammies and double whammies: The effect of length on nonword reading. *Psychonomic Bulletin and Review*, 5(2), 277-282. doi: 10.3758/BF03212951
- Rayner, K., Murphy, L. A., Henderson, J. M., & Pollatsek, A. (1989). Selective attentional dyslexia. *Cognitive Neuropsychology*, 6(4), 357-378. doi: 10.1080/02643298908253288.
- Snowling, M. (1998). Dyslexia as a phonological deficit: Evidence and implications. *Child and Adolescent Mental Health*, 3(1), 4-11, doi: 10.1111/1475-3588.00201
- Snowling, M. (2001). From language to reading and dyslexia. *Dyslexia*, 7(1), 37-46. doi: 10.1002/dys.185
- Solso, R. L., & Juel, C. L. (1980). Positional frequency and versatility of bigrams for two-through nine-letter English words. *Behaviour Research Methods & Instrumentation*, 12(3), 297-343. doi: 10.3758/BF03201669
- Stanovich, K. E. (1988). Explaining the differences between dyslexia and the garden-variety poor reader. The phonological-core variable-difference model. *Journal of Learning Disabilities*, 21(10), 590-604. doi: 10.1177/002221948802101003
- Temple, C. (1997). *Developmental cognitive neuropsychology*. Hove, East Sussex, UK: Psychology Press.
- Wagner, R., Torgesen, J., & Rashotte, C. (1999). Comprehensive Test of Phonological Processing (CTOPP). Austin, TX:PRO-ED.
- Wechsler, D. (2003). Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV). San Antonio, TX: The Psychological Corporation.

Zoccolotti, P., & Friedmann, N. (2010). From dyslexia to dyslexias, from dysgraphia to dysgraphias, from a cause to causes: A look at current research on developmental dyslexia and dysgraphia. *Cortex*, 46(10), 1211-1215. doi: 10.1016/j.cortex.2010.09.003

Chapter 6

General Discussion

General Discussion

The broad aim of this thesis was to systematically investigate the cognitive mechanisms thought to be involved in the development of letter position processing. In this concluding chapter, I will first outline the main experimental findings from the four studies reported in Chapters 2 through 5. I will then detail how these findings inform our understanding of the roles that the (1) orthographic-visual analyser, (2) orthographic input lexicon, and (3) phonological output buffer, play in both typical and atypical letter position development. I will then briefly discuss future measures that could be taken to extend the work reported in this thesis.

Overview of Main Findings

Chapter 2 reported a study that used the masked transposed-letter (TL) priming task to map the developmental trajectory of letter position coding in children learning to read (ages 7-12 years) as well as skilled adult readers. This study extended previous research by attempting to disentangle changes in letter position coding from changes in letter identity coding across development. Specifically, the influence of the TL prime on target processing (e.g., litsen - LISTEN) was measured as a cost relative to the ID prime (e.g., listen - LISTEN). Following this approach, the TL cost effect was found to increase across development, indicating that letter position coding becomes increasingly refined as reading develops.

The study reported in **Chapter 3** tested the hypothesis that changes across development in sensitivity to letter position (such as those reported in Chapter 2) are driven by lexical development, independently of maturation effects. This hypothesis was tested by investigating the influence of lexical skills on masked TL priming effects in University students, following the assumption that the relationship between lexical skill and age is far weaker in skilled adult readers than in children still undergoing reading instruction. The TL priming effect was measured as both a facilitatory effect (relative to an

ALD prime, e.g., rodgup - LISTEN), and as a cost effect (relative to an ID prime, e.g., listen - LISTEN). The results indicated no significant relationship between lexical skill and the magnitude of priming.

Chapter 4 reports on a study in which a novel variant of the Reicher-Wheeler task was developed to further investigate whether lexical development drives changes in sensitivity to letter position manipulations. The task required participants to report the identity of a letter at a specified position within three lexical contexts: anagram words (e.g., *form* – which has the anagram partner *from*), pseudowords (e.g., *pilf* – *plif*) and illegal nonwords (e.g., *ftkl* – *ftkl*). Performance for words was compared to pseudowords (the *word superiority effect*), to measure the influence of a reader's whole-word orthographic representations on letter position processing, and performance for pseudowords was compared to illegal nonwords (the *pseudoword superiority effect*), to measure the influence of a reader's knowledge of orthotactic constraints on letter position processing. The pseudoword superiority effect was found to increase with lexical skills in primary school readers (ages 7-12; Experiment 1), but the word superiority effect was only found in skilled adult readers (Experiment 2).

Chapter 5 reported a multiple single-case study including three children with developmental letter position dyslexia. Various tasks – such as visual lexical decision, reading non-migratable and migratable words, reading nonwords, same-different decision and phonological awareness – were administered to determine the locus of impairment in letter position dyslexia. The findings were most consistent with a deficit specific to the letter position coding mechanism within the orthographic-visual analyser. Both an impoverished orthographic input lexicon, and a phonological output buffer deficit, were ruled out as potential causes of letter position dyslexia.

The Orthographic-Visual Analyser

Three main findings reported in this thesis provide strong evidence in support of the idea

that separate mechanisms underpin letter position and letter identity coding. First, consistent with previous research, the studies reported in **Chapter 2** (Kezilas, McKague, Kohnen, Badcock, & Castles, submitted) and **Chapter 3** showed that both children and adults are significantly faster to make a lexical decision response when the target is preceded by a TL prime (e.g., *jugde*) than when it is preceded by a 2SL prime (e.g., *jupte*; Acha & Perea, 2008; Lupker & Davis, 2009; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2003; Ziegler, Bertrand, Lété, & Grainger, 2014). Considering the TL and 2SL prime are matched to one another on the number of letter identities in the same position as the target (e.g., both *jupte* and *jugde* have three letters in the same position as the word JUDGE), if the same mechanisms underpin letter position and identity coding then we should have found no difference between response times for the two prime conditions.

Second, the findings from the Reicher-Wheeler task showed that lexical influences on letter identity and position processing emerge at different developmental time-points (**Chapter 4**). Specifically, whilst a reader's whole-word orthographic representations were found to facilitate performance on the letter identity task in primary school readers (Chapter 4, Experiment 1), this same facilitatory effect on the letter position task did not emerge until adulthood (Chapter 4, Experiment 2). If the same cognitive mechanisms underlie letter position and identity coding, then lexical influences on the letter position and letter identity task should have emerged within a similar developmental time-frame.

The final piece of evidence in support of separate mechanisms underpinning letter position and identity coding comes from the multiple single-case study reported in **Chapter 5** (Kezilas, Kohnen, McKague, & Castles, 2014), where letter position dyslexia was found to be caused by a deficit specific to letter position coding, whilst letter identity coding remains intact. As a result of this selective deficit, the children with letter position dyslexia reported in the study made more letter position or migration errors (e.g., reading *slime* as "smile") than controls, but made a similar number of letter identity or substitution

errors (e.g., reading *beach* as “bench”). This clear dissociation between letter position and letter identity errors is difficult to account for within a model that assumes letter position and identity coding to be governed by the same mechanism.

Given these findings, it is perhaps not surprising that previous studies measuring letter position development relative to a baseline that manipulates letter identity (e.g., *jugde* vs *jupte*) have produced mixed results. Whilst some studies have reported that sensitivity to letter position manipulations increases across development (Acha & Perea, 2008; Castles, Davis, Cavalot, & Forster, 2007), others have reported that sensitivity to letter position manipulations decreases (Ziegler et al., 2014; Lété & Fayol, 2012). These mixed findings have led to two contrasting theories of letter position development. Reports of an increase across development in sensitivity to letter position have been interpreted as reflecting a refinement of the precision of letter position coding across development (Castles et al., 2007). In contrast, reports of a decrease in sensitivity to letter position have been interpreted as reflecting a developmental transition from serial letter processing – which is highly sensitive to letter position – to parallel letter processing – which prioritises rapid word retrieval over precise letter position coding (Grainger & Ziegler, 2011).

In the introduction to **Chapter 2**, I argued that resolving the mixed findings within the literature, and hence discriminating between conflicting accounts of reading development, requires measuring sensitivity to letter position manipulations against a baseline that does not manipulate letter identity. Following this premise, the study reported in **Chapter 2** was designed to map the developmental trajectory of letter position effects, independently of letter identity effects. In doing so, a clear pattern of results emerged. Specifically, sensitivity to letter position manipulations was found to increase across development, indicating that letter position coding becomes increasingly refined as reading develops.

Orthographic Input Lexicon

The findings reported in **Chapter 3** provide no evidence for lexical skill influencing the magnitude of TL priming in University students. This finding suggests that reported changes in letter position coding across development – such as those reported in **Chapter 2** – are not influenced by lexical development. In contrast, the findings from the Reicher-Wheeler task reported in **Chapter 4** revealed that lexical skills play an important role in letter position development. This discrepancy in findings is likely due to differences between the samples tested in the two studies. The study reported in **Chapter 3** included University students only, whereas the study reported in **Chapter 4** included primary school children (ages 7-12) as well as University students. Whilst several studies have shown that there is much variability in lexical skills amongst University students (e.g., Sears, Siakaluk, Chow, & Buchanan, 2008; Yap, Balota, Sibley, & Ratcliff, 2012), there is undoubtedly far more variation amongst a large sample of children at differing stages of reading development. As suggested in the discussion section of **Chapter 3**, it may have been that our inability to observe individual differences amongst participants in the magnitude of TL priming was due to the limited range of lexical skills within the sample.

One main conclusion that can be drawn from the Reicher-Wheeler findings reported in **Chapter 4** is that the quality or precision of a reader's orthographic representations, rather than just their existence, influences letter position processing. This was evidenced by the finding that the word superiority effect on the letter position task emerged later in development (adulthood) than the letter identity task (childhood). The same words were used in the letter identity and letter position tasks. Therefore, if just knowing a written word facilitates letter position processing, then the children who showed the word superiority effect in the letter identity task, should have also shown the effect in the letter position task. This interpretation is consistent with recent findings showing that letter position processing is influenced by the precision of a reader's orthographic

representations, where precise representations enable a written word to directly activate its matching orthographic representation with minimal competition from visually similar words (Andrews & Lo, 2011, see also Perfetti, 1992; Perfetti, 2007 and Ehri, 2005).

This finding also provides insights in regards to the role of the feedback mechanism between the orthographic input lexicon and the orthographic-visual analyser across development. One interpretation of the word superiority effect is that the activation of a word's orthographic representation feeds back to the orthographic-visual analyser, reinforcing the activation of the word's component letter representations (McClelland & Rumelhart, 1981). Following this theory, it could be argued that the increasing word superiority effect across development is not driven by changes occurring within the lexicon per se, but by a strengthening of the feedback mechanism between the orthographic input lexicon and the orthographic-visual analyser. The findings reported in **Chapter 4** refute this possibility. Indeed, if the increasing word superiority effect across development was driven by the strengthening of the feedback mechanism, then lexical development should have been found to influence the word superiority effect similarly for the letter identity and letter position task.

In contrast to the word superiority effect, the pseudoword superiority effect on the letter position task increased with lexical development in primary school readers (Chapter 4, Experiment 1), and was also present for skilled adult readers (Chapter 4, Experiment 2). This finding was discussed in **Chapter 4** within the context of two distinct theoretical accounts of the pseudoword superiority effect. One explanation of the pseudoword superiority effect is that it reflects perceptual fluency that is produced by familiarity of letter combinations, independently of lexical status (Grainger, Bouttevin, Truc, Bastien, & Ziegler, 2003). An alternative account, however, is that the pseudoword superiority effect is driven by the same cognitive processes that underlie the word superiority effect (Grainger & Jacobs, 1994; McClelland & Rumelhart, 1981). Specifically, the pseudoword

partially activates its real-word neighbours (e.g., *toble* would activate *table*), facilitating letter processing of the letters shared between the pseudoword and the activated word neighbour (e.g., *t*, *b*, *l*, and *e*).

How one chooses to interpret the pseudoword superiority effect has important implications for the locus of impairment in letter position dyslexia. If it is the case that the pseudoword superiority effect reflects perceptual fluency independently of lexical status (Grainger et al., 2003), then the findings reported in **Chapter 4** investigating typical letter position development align well with those reported in **Chapter 5** investigating atypical letter position development. That is, the findings from the two studies suggest that the locus of change in letter position effects as children learn to read is prelexical, and that letter position dyslexia is caused by a prelexical deficit.

However, if it is the case that the pseudoword superiority effect reflects lexical processing, then it is possible that the impairment underlying letter position dyslexia is more complex than initially thought. As previously mentioned, the findings from the word superiority effect suggest that the quality of a reader's orthographic representations (rather than just their existence) influences letter position processing. If the mechanisms underpinning the word and pseudoword superiority effect are the same (Grainger & Jacobs, 1994; McClelland & Rumelhart, 1981), then the finding that the pseudoword superiority effect on the letter position task increases with lexical development in primary school readers suggests that the development of high quality orthographic representations during the first six years of reading acquisition is critical for supporting precise letter position processing.

Whilst it was clearly demonstrated that the children with letter position dyslexia reported in **Chapter 5** have as many orthographic representations within their lexicon as their peers, the quality or precision of their orthographic representations was not assessed. Following the findings from the Reicher-Wheeler task, it could be argued that children

with letter position dyslexia have poorly defined orthographic representations that provide inadequate support for precise letter position processing. The fact that all three children were initially referred to the University for a study designed for poor spellers provides indirect support for this possibility – indeed, many words in the English language cannot be spelt correctly if a reader’s orthographic representations are ill-defined.

Of course, if it is the case that children with letter position dyslexia do have poorly defined orthographic representations, then it is unclear as to whether this is the cause or result of their letter position deficit. It could be that poorly defined orthographic representations cause the excessive letter position errors made by children with letter position dyslexia. Alternatively, letter position dyslexia could be caused by a letter position coding deficit within the orthographic-visual analyser, and this deficit hinders the development of fully specified orthographic representations. Future research may therefore seek to better understand the complex relationship between the orthographic-visual analyser and the orthographic input lexicon in both typical and atypical reading development.

The Phonological Output Buffer

The role of the phonological output buffer in letter position dyslexia was assessed in **Chapter 5**. Specifically, I tested whether the elevated tendency for children with letter position dyslexia to make letter position errors is caused by a deficit specific to the assembling of phonemes in their correct order. Consistent with previous research, it was found that the letter position errors made by children with letter position dyslexia were not due to a phonological output buffer deficit (Friedmann & Rahamim, 2007; Kohnen, Nickels, Castles, Friedmann, & McArthur, 2012). This was evidenced by the finding that the children with letter position dyslexia were within the average range on standardised tests that draw heavily on the resources of the phonological output buffer. This finding joins a growing body of research indicating that not all dyslexias are caused by an

underlying phonological deficit (see Zoccolotti and Friedmann, 2010 for a review).

The role of the phonological output buffer in letter position effects in typical readers was not investigated in this thesis. However, our findings suggest that if the phonological output buffer is implicated in letter position effects in reading aloud, then its role is in addition to the role of the orthographic-visual analyser and orthographic input lexicon. This claim is supported by the strong letter position effects reported in all four studies on tasks that do not require spoken output, such as the lexical decision task, the Reicher-Wheeler task, and the same-different decision task.

Conclusion and Future Directions

The experiments reported in Chapters 2 through 5 were designed to isolate the cognitive mechanisms thought to be involved in letter position effects across development. Specifically, **Chapter 2** was designed to investigate the development of letter position coding independently of letter identity coding; **Chapter 3** and **4** were designed to investigate the influence of the developing orthographic input lexicon on letter position processing, independently of other factors, such as the general maturation of the visual system; and **Chapter 5** was designed to isolate the impairment in children with letter position dyslexia by exploring the role of the orthographic-visual analyser, the orthographic input lexicon, and the phonological output buffer in their excessive letter position errors.

The comprehensive investigation of letter position processing reported in this thesis has the potential to inform future research directions. For example, the data reported here could provide a useful starting point from which to model the mechanisms underpinning letter position processing in children who are learning to read. At present, only verbal theories of letter position processing in reading development exist (e.g., Castles et al., 2007; Grainger & Ziegler, 2011). Computational models have the advantage over verbal theories in that they can be used to simulate human data, enabling specific hypotheses to

be formed in regards to how individuals with typical and impaired reading will perform on a task. Given the complex relationship between the orthographic-visual analyser and the orthographic input lexicon discussed in this thesis, the level of specificity unique to computational modelling may be required if we are to ever fully understand the intricacies of letter position processing in developing readers.

The complexity of the findings reported in this thesis suggest that we have only just begun to scratch the surface of what is to be discovered about letter position processing in developing and skilled readers. It is therefore hoped that the work presented in this thesis will stimulate more research in this somewhat under-explored aspect of reading development.

References

- Acha, J., & Perea, M. (2008). The effects of length and transposed-letter similarity in lexical decision: Evidence with beginning, intermediate, and adult readers. *British Journal of Psychology*, 99, 245-264. doi: 10.1348/000712607X224478
- Andrews, S., & Lo, S. (2012). Not all skilled readers have cracked the code: individual differences in masked form priming. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 38(1), 152-163. doi: 10.1037/a0024953
- Castles, A., Davis, C., Cavalot, P., & Forster, K. (2007). Tracking the acquisition of orthographic skills in developing readers: Masked priming effects. *Journal of Experimental Child Psychology*, 97, 165-182. doi:10.1016/j.jecp.2007.01.006
- Ehri, L. C. (2005). Learning to read words: Theory, findings, and issues. *Scientific Studies of Reading*, 9(2), 167-188.
- Friedmann, N., and Rahamim, E. (2007). Developmental letter position dyslexia. *Journal of Neuropsychology* 1, 201-236. doi: 10.1348/174866407X204227
- Grainger, J., Bouttevin, S., Truc, C., Bastien, M., & Ziegler, J. (2003). Word superiority, pseudoword superiority, and learning to read: A comparison of dyslexic and normal readers. *Brain and Language*. 87, 432-440. doi: 10.1016/S0093-934X(03)00145-7
- Grainger, J., & Jacobs, A. M. (1994). A dual read-out model of word context effects in letter perception: Further investigations of the word superiority effect. *Journal of Experimental Psychology: Human Perception and Performance*, 20(6), 1158-1176
- Grainger, J., & Ziegler., J. C. (2011). A dual-route approach to orthographic processing. *Frontiers in Psychology*, 2(54), 1-13, doi: 10.3389/fpsyg.2011.00054
- Kezilas, Y., Kohnen, S., McKague, M., Castles, A. (2014). The locus of impairment in developmental letter position dyslexia. *Frontiers in Human Neuroscience*, 8(356), 1-14. doi: 10.3389/fnhum.2014.00356

- Kezilas, Y., McKague, M., Kohnen, S., Badcock, N. A., & Castles, A. (submitted, 2015).
Disentangling the developmental trajectories of letter position and letter identity
coding using masked priming. *Journal of Experimental Psychology: Learning,
Memory and Cognition*.
- Kohnen, S., & Castles, A. (2013). Pirates at parties: Letter position processing in
developing readers. *Journal of Experimental Child Psychology*, 50(14), 3681-3692.
doi: <http://dx.doi.org/10.1016/j.jecp.2012.08.011>
- Kohnen, S., Nickels, L., Castles, A., Friedmann, N., McArthur, G. (2012). When ‘slime’
becomes ‘smile’: developmental letter position dyslexia in English.
Neuropsychologia, 50(14), 3681-3692. doi:
10.1016/j.neuropsychologia.2012.07.016
- Lété, B., & Fayol, M. (2013). Substituted-letter and transposed-letter effects in a masked
priming paradigm with French developing readers and dyslexics. *Journal of
Experimental Child Psychology*, 114(1), 47-62. doi: 10.1016/j.jecp.2012.09.001
- Lupker, S. J., & Davis, C. J. (2009). Sandwich priming: a method for overcoming the
limitations of masked priming by reducing lexical competitor effects. *Journal of
Experimental Psychology: Learning, Memory and Cognition*, 35(3), 618-639. doi:
10.1037/a0015278
- Lupker, S. J., Perea, M., & Davis, C. (2008). Transposed-letter effects: Consonants, vowels
and letter frequency. *Language and Cognitive Processes*, 23(1), 93-116. doi:
10.1080/01690960701579714
- McClelland, J. L., Rumelhart, D. E. (1981). An interactive activation model of context
effects in letter perception: Part 1. An account of basic findings. *Psychological
Review*, 88, 375-407
- 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. doi: 10.1080/09541440701306941
- Perfetti, C. A. (1992). The representation problem in reading acquisition. In P. B. Gough, L.C. Ehri, & R. Treiman (Eds.), *Reading acquisition*. Hillsdale, NJ: Erlbaum.
- Perfetti, C. A. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading*, 11(4), 357-383. doi:10.1080/10888430701530730
- Sears, C. R., Siakaluk, P. D., Chow, V. C., & Buchanan, L. (2008). Is there an effect of print exposure on the word frequency effect and the neighbourhood size effect? *Journal of Psycholinguistic Research*, 37(4), 269–291.
- Yap, M.J., Balota, D.A., Sibley, D.E., & Ratcliff, R. (2012). Individual differences in visual word recognition: Insights from the English Lexicon Project. *Journal of Experimental Psychology: Human Perception and Performance*, 38(1), 53-79. doi: 10.1037/a0024177
- Ziegler, J. C., Bertrand, D., Lété, B., & Grainger, J. (2014). Orthographic and phonological contributions to reading development: Tracking developmental trajectories using masked priming. *Developmental Psychology*, 50(4), 1026-1036. doi: 10.1037/a0035187
- Ziegler, J. C., & Jacobs, A. M. (1995). Phonological information provides early sources of constraint in the processing of letter strings. *Journal of Memory and Language*, 34(5), 357-593. doi: 10.1006/jmla.1995.1026
- Zoccolotti, P., & Friedmann, N. (2010). From dyslexia to dyslexias, from dysgraphia to dysgraphias, from a cause to causes: A look at current research on developmental dyslexia and dysgraphia. *Cortex*, 46(10), 1211-1215. doi: 10.1016/j.cortex.2010.09.003



The locus of impairment in English developmental letter position dyslexia

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Many children with reading difficulties display phonological deficits and struggle to acquire non-lexical reading skills. However, not all children with reading difficulties have these problems, such as children with selective letter position dyslexia (LPD), who make excessive migration errors (such as reading *slime* as “smile”). Previous research has explored three possible loci for the deficit – the phonological output buffer, the orthographic input lexicon, and the orthographic-visual analysis stage of reading. While there is compelling evidence against a phonological output buffer and orthographic input lexicon deficit account of English LPD, the evidence in support of an orthographic-visual analysis deficit is currently limited. In this multiple single-case study with three English-speaking children with developmental LPD, we aimed to both replicate and extend previous findings regarding the locus of impairment in English LPD. First, we ruled out a phonological output buffer and an orthographic input lexicon deficit by administering tasks that directly assess phonological processing and lexical guessing. We then went on to directly assess whether or not children with LPD have an orthographic-visual analysis deficit by modifying two tasks that have previously been used to localize processing at this level: a same-different decision task and a non-word reading task. The results from these tasks indicate that LPD is most likely caused by a deficit specific to the coding of letter positions at the orthographic-visual analysis stage of reading. These findings provide further evidence for the heterogeneity of dyslexia and its underlying causes.

Keywords: phonological output deficit, orthographic input lexicon deficit, orthographic-visual analysis deficit, migration errors, substitution errors, developmental dyslexia

INTRODUCTION

The last three decades have seen an emphasis on the role that impaired phonological processing plays in developmental dyslexia. Various researchers have posited that at the core of dyslexia lies an impairment in the ability to represent, store, and retrieve speech sounds (Stanovich, 1988; Snowling, 1998, 2001; Ramus, 2003). This phonological deficit is proposed to be linked to the difficulty children with dyslexia experience in learning the mappings between letters and speech sounds, which is often remediated using phonics training (see Castles et al., 2009; McArthur et al., 2012). The phonological deficit account of dyslexia is supported by a multitude of correlational, longitudinal, and training studies that have found developmental dyslexia to typically be associated with poor phonological awareness (e.g., Høien et al., 1989), slow lexical retrieval skills (e.g., Denckla and Rudel, 1976), and poor verbal short-term memory (e.g., Mann et al., 1980; Mann and Liberman, 1984).

However, not all children with dyslexia have a phonological impairment. For example, children with surface dyslexia appear to have no difficulties with mapping letters onto speech sounds, as is evidenced by their ability to read non-words as proficiently as their peers (e.g., Castles and Coltheart, 1993; Broom and Doctor, 1995; Castles and Coltheart, 1996; Temple, 1997). Instead, surface dyslexics have been thought to have problems with orthographic

processing, resulting in excessive reading errors where an irregular word is sounded out incorrectly using common letter-sound rules (e.g., *yacht* is read as if it rhymed with *matched*). The existence of cases of developmental dyslexia where phonological processing appears intact suggests that while some dyslexias may be attributed to an impairment in phonological processing, other dyslexias are not. Here, we provide further evidence for the heterogeneity of dyslexia and its underlying causes by furthering the investigation of the locus of impairment in English-speaking children with developmental letter position dyslexia (LPD).

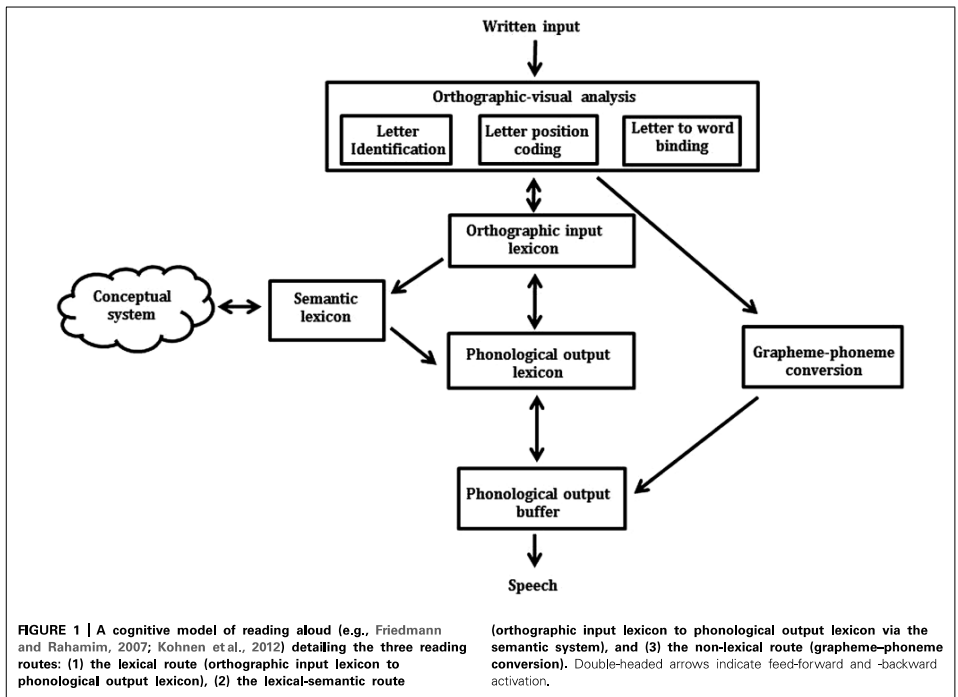
The hallmark symptom of LPD is an elevated tendency to make “migration errors,” where the order of letters within migratable words (more commonly known as anagrams) is confused, resulting in the misreading of a word as its migration partner (e.g., *slime* is read as “smile”). While migration errors are frequently made by beginning readers (Kohnen and Castles, 2013), English children with LPD have been found to make up to four times the number of migration errors made by their peers (Kohnen et al., 2012). Children with LPD have particularly high migration error rates when reading words where the transposition of letters in the middle of a word can lead to another word (e.g., *slime-smile, diary-dairy*). Intriguingly, cases of selective LPD have been documented, where all other reading processes appear intact (Friedmann and Rahamim, 2007; Kohnen et al., 2012). Children

with selective LPD read as accurately and as fluently as their peers – except when they are asked to read migratable words.

There are four studies that have investigated the locus of impairment in developmental LPD – two in Hebrew (Friedmann and Rahamim, 2007; Friedmann et al., 2010a), one in Arabic (Friedmann and Haddad-Hanna, 2012), and most recently one in English (Kohnen et al., 2012). All four studies have used the cognitive model of reading aloud illustrated in Figure 1 to identify the locus of impairment in LPD. Following this model, when a word is encountered in print, its visual properties undergo orthographic-visual analysis. This stage involves identifying the word's letters, coding the position of the letters within the word, and binding the letters to the word. Following these initial computations, the word 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 phonological output lexicon via the semantic system), and (3) the non-lexical route (grapheme-phoneme conversion). Typically, the lexical and lexical-semantic routes successfully process all words within a reader's orthographic input lexicon (storage for familiar words) but fail to process non-words. In contrast, the non-lexical route successfully sounds out non-words and words that follow typical letter to sound rules ("regular words" such as *surf*, *blame*, and

hand), but fails to provide accurate pronunciation for irregular words (such as *yacht*, *come*, and *friend*). According to the model, after the written input has progressed through these routes, the phonemes that make up the word are assembled and held active in the phonological output buffer until a verbal response is made.

Using this model, previous research has proposed three possible loci for the migration errors seen in LPD (Friedmann and Rahamim, 2007; Kohnen et al., 2012). First, the migration errors may occur at the phonological output buffer as the phonological code is being prepared for pronunciation. Strong evidence against this hypothesis comes from the observation that children with LPD perform within the average range on standardized tests that draw heavily on the phonological output buffer (e.g., phonological awareness and verbal short-term memory assessments; Friedmann and Rahamim, 2007; Kohnen et al., 2012). Furthermore, Kohnen et al. (2012) reported that the majority of the migration errors made by their sample of English LPDs could not be attributed to the swapping of phonemes in the output buffer. For example, the swapping of the phonemes in *cloud* (/k/ /l/ /aw/ /d/) does not create the migration error "could" (/k/ /u/ /d/; Kohnen et al., 2012). Rather, the deficit causing this error must occur before the graphemes in the word have been converted into their appropriate phonemes.



Second, migration errors may occur due to an orthographic input lexicon deficit. On this account, LPDs are proposed to have fewer lexical entries in their orthographic input lexicon (i.e., have a smaller sight-word vocabulary) than is typical for their age. When the lexical entry matching a target word cannot be found in the lexicon, a lexical guessing strategy is adopted resulting in an error that is visually similar to the target word. This possibility is unlikely however, as LPDs have been found to read non-migratable, irregular words (e.g., *yacht*) as proficiently as their peers, indicating that their orthographic input lexicon is intact (Friedmann and Rahamim, 2007; Kohnen et al., 2012). Furthermore, if the migration errors made by LPDs are the result of lexical guessing, they should also make other lexical similarity errors, such as substitution errors (e.g., reading *slime* as “slide”). This is not the case – their reading errors appear to be selective to the transposition of letters within words (Friedmann and Rahamim, 2007; Kohnen et al., 2012).

The third and final possibility following Figure 1 is that LPD is caused by a deficit specific to the coding of letter positions within words at the orthographic-visual analysis stage of reading. Of the three possible deficits (phonological output buffer, orthographic input lexicon, and orthographic-visual analysis), an orthographic-visual analysis deficit currently provides the most parsimonious explanation for the available data. Two pieces of evidence suggest that LPD is caused by an orthographic-visual analysis deficit. First, in Hebrew, LPDs have been found to make excessive migration errors on a same-different decision task (e.g., responding “same” to *slime-smile*; Friedmann and Rahamim, 2007; Friedmann et al., 2010a). Two of the three cases of English LPD reported by Kohnen et al. (2012) also showed this effect. Because the same-different decision task is thought to tap prelexical processing (see Besner et al., 1984; Kinoshita and Norris, 2009), LPDs’ poor performance on this task has been taken as evidence for an orthographic-visual analysis deficit (Kohnen et al., 2012). Second, in Hebrew, LPDs have been found to make more word responses to migratable items (e.g., reading *slime* as “smile,” and *forg* as “frog”) as well as non-word responses (e.g., reading *pilf* as “plif”), indicating that the cognitive mechanism that is defective in LPD is common to both lexical and non-lexical routes (Friedmann and Rahamim, 2007). There are two components of the model that are common to both routes: orthographic-visual analysis and the phonological output buffer. As previously outlined, there is strong evidence refuting a phonological output buffer deficit account of LPD. Therefore, the finding that LPDs in Hebrew make more word and non-word responses to migratable items has been taken as evidence for an orthographic-visual analysis deficit, which then has knock on effects to both lexical and non-lexical reading.

There are, however, two pieces of data that appear inconsistent with an orthographic-visual analysis deficit account of English LPD. First, one of the three LPD cases reported by Kohnen et al. (2012) did not make excessive migration errors on a same-different decision task. As the same-different decision task should reveal an orthographic-visual analysis deficit, this finding may suggest that the migration errors made by this case (identified as EL) are not caused by this deficit. Second, while the LPDs in Kohnen et al.’s (2012) study made more word

responses to migratable items (e.g., reading *slime* as “smile,” and *forg* as “frog”) than controls, they did not make more non-word migration responses than controls (e.g., reading *pilf* as “plif”). This finding proves problematic for an orthographic-visual analysis deficit account of English LPD, as a deficit at the initial, orthographic-visual analysis stage of reading should produce migration errors in both lexical and non-lexical reading. The aim of the present study was to follow up on these two unexpected findings to clarify the locus of impairment in English LPD.

One plausible reason why EL did not make excessive migration errors on the same-different decision task is that he was adopting a strategy during the task whereby he compared each letter across the two words. In Kohnen et al.’s (2012) task, participants were presented with two words side by side, and were given as much time as they needed to make their response. As Kohnen et al. (2012) have suggested, these task conditions give participants the opportunity to compare each letter across the two words, rather than comparing the two words to one another as is intended by the task. If attention is focused on each individual letter, each letter’s position is no longer processed in relation to the position of the other letters within the word. This means that letter positions will less likely be confused, and migration errors will less likely be made.

Additionally, there are two plausible reasons why the LPDs in Kohnen et al.’s (2012) study may not have made excessive non-word migration responses, where the order of letters in a non-word stimulus is confused, resulting in a non-word response (e.g., reading *pilf* as “plif”). First, while letters in familiar words are thought to be processed in parallel via the lexical routes, letters in non-words are thought to be processed serially via the non-lexical route (Rastle and Coltheart, 1998; Friedmann and Rahamim, 2007). The serial processes that underpin non-word reading might therefore reduce the likelihood that an LPD will make non-word migration errors (Friedmann and Rahamim, 2007; Kohnen et al., 2012). Second, research in both Hebrew and English has shown that there are specific variables that influence whether or not LPDs make word migration errors. For example, LPDs are most likely to make a word migration error when a low-frequency word can migrate into a higher frequency word via the transposition of two adjacent, internal letters [e.g., reading *trail* (frequency = 18) as “trial” (frequency = 58)]. It is plausible, therefore, to hypothesize that there is also a set of variables that influence whether a non-word migration error will be made, and that variation across item sets on such variables might account for differences in results.

THE PRESENT STUDY

The aim of this multiple single-case study with three English-speaking LPDs was to replicate and extend previous research regarding the locus of impairment in LPD.

First, we aimed to replicate previous findings suggesting that LPD is not caused by a phonological output buffer deficit. We then sought to replicate the finding that the migration errors seen in LPD are not the result of lexical guessing due to an orthographic input lexicon deficit.

Following this, we aimed to address two findings that appear to be inconsistent with an orthographic-visual analysis deficit

account of LPD. The first inconsistent finding is that EL, one of Kohnen et al.'s (2012) LPDs, did not make more migration errors on a same-different decision task than controls. The second finding that appears at odds with this account is that all three LPDs in Kohnen et al.'s (2012) study did not make more non-word migration responses (e.g., reading *pilf* as “plif”) than controls. The present study therefore aimed to extend Kohnen et al.'s (2012) study by modifying the same-different decision task and the non-word reading task in an attempt to clarify the locus of impairment. Specifically, we extended Kohnen et al.'s (2012) work by (1) administering a sequential presentation variant of the same-different decision task, (2) including a consonant-string condition in the same-different decision task, and (3) manipulating the bigram frequency of the non-words presented in the reading aloud task.

A sequential variant of the same-different decision task was administered to eliminate a possible letter-by-letter matching strategy. That is, rather than presenting the words side by side, where a direct comparison between each word's letters can be made, we presented items one after the other. Under sequential presentation, we expected all three LPDs in the present study to be significantly poorer than controls at detecting when two migratable words are different. To provide a further test of the orthographic-visual analysis deficit account of LPD, we included a consonant-string condition in the task. If LPD is due to a letter position coding deficit at the orthographic-visual analysis stage of reading, then LPDs should be poorer than controls at identifying when two migratable items are different from one another, regardless of the lexicality of the items.

In the present study, we also manipulated the bigram frequency of the non-words in the reading aloud task. One plausible reason why Kohnen et al.'s (2012) LPDs did not make more non-word migration errors than controls when reading aloud non-words (e.g., reading *pilf* as “plif”) is that there may be various factors that influence whether or not a non-word migration error will be made. Previous research has shown that the written frequency of a word's migration counterpart, relative to the item itself, influences whether or not a migration error will be made. For example, Friedmann and Gvion (2001) found that the most common migration error made by LPDs was the reading of a non-word (which by definition has a written frequency of 0) as a word (e.g., *coisun* read as “cousin”). The next most common migration error was the reading of a word as its higher frequency counterpart [e.g., *trail* (frequency = 18) read as “trial” (frequency = 58)]. Following these findings, it is plausible to hypothesize that the bigram frequency of the non-word migration counterpart, relative to the bigram frequency of the non-word itself, will influence whether or not a non-word migration error will be made. Our exploratory hypothesis was therefore that LPDs would be more likely to migrate a low bigram frequency non-word into its higher bigram frequency non-word counterpart [e.g., reading *plif* (BF = 180) as “pilf” (BF = 1251)].

MATERIALS AND METHODS

Ethics approval for this project was granted by Macquarie University Human Research Ethics Committee. Participants and their

parents gave verbal and written consent to their involvement in the study.

PARTICIPANTS

Participants in this study were three children: LM, EL, and LL. LM, was a 9-year 8-month-old girl in her second semester of grade 4 when we first met her and was homeschooled by her mother¹. EL was a participant in Kohnen et al.'s (2012) study and was recruited for the present study when he was 9 years 8 months old and about to commence grade 5 at a mainstream school. Our third participant, LL, was an 11-year 9-month-old girl who had commenced grade 7 at a mainstream school two weeks before we met her.

All three children were initially referred to us because their parents were concerned about their spelling ability. Their reading skills were reported by their parents to be within the average range for their age. Both LM and LL's hearing and vision were reported as normal. EL had long-sightedness and astigmatism, which were corrected for with glasses. He had also been diagnosed with pendular nystagmus (involuntary repetitive rhythmic movement of eyes from side to side). All three children had no diagnoses of developmental delay or difficulties [e.g., AD(H)D, SLI].

Each LPD's performance on the standardized tests used to assess for a phonological output buffer deficit was compared to the test's age-appropriate normative data. Each LPD's performance on the experimental tasks was compared to a control group of average readers without LPD. We recruited two different grade-matched control groups. Six grade 4 controls were used as a control group for LM and EL (M age = 10 years 1 month, SD age = 2 months). Two grade 6 controls and three grade 7 controls were used as a control group for LL (M age = 12 years 3 months, SD age = 7 months).

PROCEDURE

Participants were tested over multiple testing sessions at Macquarie University. Testing sessions went for between 90–150 min in length including breaks. All relevant property statistics for the experimental tasks were derived from N-Watch (Davis, 2005). All experimental reading aloud tasks and the visual lexical decision task were administered using flash cards. Unless otherwise specified, Crawford and Garthwaite's (2002) t -test was used to compare each LPD's task performance to controls, and Fisher's exact was used to compare each LPD's performance on one condition to another condition.

RESULTS

TESTS DETERMINING ELIGIBILITY

LM, EL and LL were identified as having LPD based on their scores on the Letter Position Test (LetPos: Kohnen et al., 2014). The LetPos is a reading aloud test consisting of 60 anagram words (30 anagram pairs, e.g., *slime* – *smile*), presented over two pages. There are three types of errors that can be made on this test: “migration errors” (reading a word as its migration partner, e.g., reading *slime* as “smile”), “word errors” (reading a word as any word other than its migration partner, e.g., reading *slime* as “slide”), and “other

¹Homeschooling for LM followed a strict and regulated curriculum matched to mainstream education. The work completed by home-schooled students has to be documented and monitored regularly.

errors" (reading a word as a non-word, e.g., reading *slime* as "slome"). The normative data for the LetPos was collected in the final term of the school year. LPDs were selected on the basis that their LetPos performance was more than one standard deviation below the mean for "migration errors," and within one standard deviation of the mean for "word errors" and "other errors," when compared to the grade-appropriate normative data.

LPD participants were also selected to have no obvious reading problems, other than the reading of migratable words. Specifically, they were selected only if they had normal irregular word and non-word reading, as assessed by the Castles and Coltheart Reading Test (CC2; Castles et al., 2009). Both LM and EL were within the average range for their age (an *z*-score between -1 and $+1$) on both the irregular word and non-word reading components of the test. While LL was within the average range on the irregular word component of the CC2, she was below average on the non-word reading component of the test². She was included in the study, however, because her non-word reading errors appeared to stem from an underlying problem with reading letters in their correct order. For example, LL made non-word migration errors such as reading *borp* as "brop." When these migration errors were removed from her score, her non-word reading was within the average range.

Control participants were selected to be average on the irregular word and non-word reading subtests of the CC2 and to be within one standard deviation of the mean on each component (migration, word and other errors) of the LetPos.

ASSESSING THE PHONOLOGICAL OUTPUT BUFFER

A phonological output deficit should manifest itself in poor performance on tasks that require phoneme production and/or manipulation. To investigate whether LPD is caused by a phonological output buffer deficit, LM, EL and LL were assessed on

phonological awareness, speed of lexical retrieval and verbal short-term and working memory. If their migration errors are caused by a phonological output buffer deficit, they should be below average on these tasks compared to age-appropriate normative data.

Phonological awareness was assessed using the Segmenting Non-words and Phoneme Reversals subtests of the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999). In the Segmenting Non-words subtest children are given a series of non-words, which they are asked to repeat, and then say one sound at a time (e.g., "dray, d – r – ay"). In the Phoneme Reversal subtest children are asked to first repeat a non-word, and then to reverse the sounds to make it sound like a real word (e.g., "nus, sun").

Speed of lexical retrieval was assessed using the Rapid Naming subtests of the CTOPP. LPDs were assessed on their ability to rapidly name letters, digits, objects and colors, which were each assessed separately. In these subtests, LPDs were asked to name 36 items presented on a single page as quickly as they could.

The Repetition of Nonsense Words subtest of the NEPSY (Korkman et al., 1998) and the Digit Span subtest of the Wechsler Intelligence Scale for Children Fourth Edition (WISC-IV; Wechsler, 2003) were used to assess verbal short-term and working memory. In the Repetition of Nonsense Words subtest, children are asked to repeat non-words (e.g., *bu-leks-tis*). The Digit Span subtest has two components – Forward Digit Span, and Backwards Digit Span. In the Forward Digit Span children are asked to repeat strings of digits in the same order as they heard them, and in the Backwards Digit Span subtest children have to repeat strings of digits in reverse order.

Table 1 shows that all LPD participants were within (or even above) the average range (*z*-score between -1 and $+1$) on all nine measures of phonological processing. In addition LM, EL, and LL were asked to orally repeat the words after the experimenter for which they had previously made a migration error on in a reading aloud task. Each LPD performed this task without making a single migration error.

²Note that there are currently no normative data published for children who are LL's age (11 years 9 months). LL's performance on the CC2, as well as that of her control group, was therefore compared to the normative data of children between the ages 11 years and 11 years 5 months.

Table 1 | Z scores on standardized tests used to assess for a phonological output deficit (average range is between -1 and $+1$).

		LM	EL	LL
Phonological awareness	Segmenting nonwords (CTOPP)	0.33	1.67	1.67
	Phoneme reversals (CTOPP)	0.33	0.67	-0.67
Lexical retrieval	Rapid naming (CTOPP)			
	Digits	1.33	0.33	-0.67
	Letters	1.00	0.67	-1.00
	Colors	1.00	0.33	-1.00
	Objects	1.33	-0.67	-0.33
Verbal memory	Digit span (WISC-IV)			
	Forward	1.00	0.33	1.00
	Backward	0.00	-0.33	0.67
	Repetition of nonsense words (NEPSY)	1.00	1.00	0.33

Taken together, these findings indicate that the migration errors made by the three LPDs in the present study cannot be attributed to a phonological output buffer deficit.

ASSESSING THE ORTHOGRAPHIC INPUT LEXICON

To investigate whether LM, EL and LL have an orthographic input lexicon deficit we administered a reading aloud non-migratable, irregular words task. Irregular words were used to ensure that access to the orthographic input lexicon was obligatory for a correct response to be made. If LPDs have an orthographic input lexicon deficit, they should be poorer at this task than controls.

To explicitly test whether their excessive migration errors are the result of lexical guessing, we administered two tasks: a reading aloud migratable and substitution words task, and a visual lexical decision task. If LPDs' migration errors are the result of lexical guessing, they should make more substitution errors than controls on a reading aloud task (e.g., reading *track* as "trick"), as well as more substitution errors on a visual lexical decision task (e.g., accepting *esho* (derived from *echo*) as a word).

Reading non-migratable, irregular words

Participants were asked to read aloud 87 non-migratable words which were selected to contain at least one letter-sound rule that was atypical (e.g., pearl, cousin) according to Reggelex (Baayen et al., 1995), a program used to compute the rule based pronunciation of a letter-string (Coltheart et al., 2001). Because we were interested in each LPD's lexical reading skills, errors that appeared to stem from a difficulty in ordering letters in words (e.g., reading *chalk* as "chlak") were removed from the error analysis. Both LM and EL made 12.64% errors on this task, which was not significantly different from their control group, who made 9.58% errors (SD = 2.48%; $t = 1.14$, $p = 0.15$ one-tailed). LL made 6.90% errors on this task, which was not significantly different from her control group who made 8.28% errors (SD = 2.36%; $t = 0.53$, $p = 0.31$ one-tailed).

Eighteen of the 87 experimental words were items that had already been administered in the irregular word reading component of the CC2. We therefore conducted an additional analysis including irregular words that were not part of the CC2 ($N = 69$). All three LPD's made as many errors as controls in this additional analysis (all $p > 0.15$ one-tailed).

This finding suggests that LM, EL and LL have as many entries in their orthographic input lexicon as controls, and that they have no difficulty in accessing these entries.

Reading aloud migratable and substitution words

Participants read aloud 58 migratable words, which were created from 29 word pairs that were different via the transposition of two internal letters (e.g., *slime-smile*). Migratable words were intermixed with 30 substitution words created from 15 pairs of words that were different via the substitution of a single internal letter (e.g., *track-trick*). Substitution words were matched as closely as possible to migratable words on length (migratable: $M = 5.07$, $SD = 0.53$; substitution: $M = 5.07$, $SD = 0.69$), relative written frequency between a word and its partner (migratable: $M = 27.51$, $SD = 36.83$; substitution: $M = 36.61$, $SD = 36.62$), and the number of substitution neighbors (migration: $M = 4.86$, $SD = 3.48$; substitution: $M = 4.90$, $SD = 3.18$). The item pairs were presented over separate tasks such that participants did not read a word and its partner in the same task. These words were intermixed with 122 words, which were not used to address the research questions in the present study.

Three error types were analyzed: (1) migration errors, where a migratable word was read as its partner, (2) substitution errors, where a substitution word was read as its partner, and (3) "N" errors, which included substitution errors (e.g., reading *slime* as "slide"), addition errors (reading *slime* as "slimes"), and deletion errors (reading *slime* as "slim") made on all migratable and substitution words. Incorrect reading responses that were potentially due to sounding the word out rather than one of these three error types (e.g., reading *bread* as "breed") were not included in the analysis.

The results are outlined in Table 2. All three LPDs made more migration errors than controls (LM: $t = 21.95$, $p < 0.001$ one-tailed; EL: $t = 9.49$; $p < 0.001$ one-tailed; LL: $t = 4.81$, $p < 0.01$ one-tailed). Because there was no variance in the number of substitution errors made by controls, a Fisher's exact test was used (instead of Crawford's t -tests) to compare LPDs' performance to their respective control groups. All three LPDs made as many substitution errors as controls (all $p > 0.5$ one-tailed). Both LM and EL made as many N errors as controls (both $t = 1.11$, $p = 0.16$ one-tailed). Because there was no variance in the number of N errors made by LL's control group, a Fisher's exact test was used instead of Crawford's t -test, which indicated that she made as many N errors on the task as controls ($z = 0.71$, $p = 0.24$ one-tailed).

The finding that LM, EL and LL's reading errors were selective to the migration of letters within words suggests that their LPD cannot be attributed to lexical guessing.

Table 2 | Percentage of errors on reading aloud words in the migration and substitution conditions.

	LM	EL	LM and EL controls	LL	LL controls
Migration errors	27.59***	15.52***	6.32 (0.89)	12.07**	2.07 (1.89)
Substitution errors	3.33	0.00	0.00 (0.00)	0.00	0.00 (0.00)
N errors	2.27	2.27	0.95 (1.12)	2.27	0.00 (0.00)

Numbers in parentheses denote standard deviation of the mean for control groups.
** $p < 0.01$, *** $p < 0.001$ compared to control group.

Visual lexical decision

A visual lexical decision task was also administered to determine whether migration errors made by LPDs were the result of lexical guessing. Forty non-migratable words formed the word condition in this task. Three non-word conditions were created by modifying the word items – a migratable non-word condition (*coisun* (derived from *cousin*); $N = 16$), a single-substitution non-word condition (*eamly* (derived from *early*), $N = 12$), and a double-substitution non-word condition (*provere* (derived from *private*); $N = 12$). Single and double substitution items were included because both have previously been used in research as a comparison condition for migratable items (e.g. Perea and Lupker, 2004; Perea and Fraga, 2006; Beyersmann et al., 2011, 2012, 2013).

Items in the migratable non-word condition were matched as closely as possible to items in the single- and double-substitution condition on bigram frequency (migration condition: $M = 719.04$, $SD = 415.91$; single-substitution condition: $M = 578.54$, $SD = 336.08$; double-substitution condition: $M = 713.68$, $SD = 553.36$), and the written frequency of the words that they were derived from (migratable $M = 87.56$, $SD = 125.20$; single-substitution: $M = 96.89$, $SD = 116.29$; double-substitution: $M = 72.64$, $SD = 112.39$). Words and non-words were intermixed with 112 additional items, which were not used to address the research questions in the present study. Items were presented over two separate tasks, such that a non-word and the word it was derived from were not presented in the same task.

So that we could be relatively certain that a “word” response to a non-word was due to the participant misreading the non-word as the word it was derived from, non-words in the migration condition and the double-substitution condition did not have a single substitution neighbor. Furthermore, the non-words in the single substitution condition did not have a single substitution neighbor other than the word that they were derived from. To further ensure that participants’ “word” responses were due to their misreading of the non-word as its word partner, we removed non-words derived from words that participants did not know. We determined whether or not a participant knew a word based on their performance on the “word” condition of the visual lexical decision task, and their reading aloud of these words. If a participant could not read aloud the word *and* did not recognize the word in the visual lexical decision task, the word was defined as unknown, and hence its non-word counterpart was removed from their individual analysis. This comprised 5.00% of LM’s data, 2.50% of EL’s data, and 2.92% ($SD = 3.68\%$) of their control group’s data. For LL, 2.50% of her data was removed, and 1.00% ($SD = 2.24\%$) of her control group’s data was removed.

The results are outlined in Table 3. All three LPDs accepted more migratable non-words as words than controls (LM: $t = 3.59$, $p = 0.01$ one-tailed; EL: $t = 2.59$, $p = 0.02$ one-tailed; LL: $t = 2.90$, $p = 0.02$ one-tailed). Both EL and LL accepted as many single and double substitution non-words as words as controls (both $t < 1.12$, $p > 0.16$ one-tailed). LM, however, accepted more single and double substitution non-words as words than controls (single: $t = 2.51$, $p = 0.03$ one-tailed; double: $t = 4.54$, $p = 0.003$ one-tailed).

The finding that EL and LL’s excessive errors on the visual lexical decision task were selective to the migration condition suggests that their migration errors are not the result of lexical guessing. In contrast, LM’s excessive errors on the task were not selective to the migration condition – she also made more substitution errors on the task than controls. This finding suggests that a lexical guessing strategy may have been the cause of LM’s migration errors on the visual lexical decision task.

ASSESSING THE ORTHOGRAPHIC-VISUAL ANALYSIS STAGE OF READING

To investigate whether LPD is caused by an orthographic-visual analysis deficit, we administered a sequential same-different decision task and a reading aloud non-words task. If LPD is caused by an orthographic-visual analysis deficit, LPDs should make more migration errors than controls on tasks that tap prelexical processing (e.g., same-different decision) since orthographic-visual analysis is a prelexical process. Furthermore, if their migration errors are caused by an orthographic-visual analysis deficit, LPDs should make more migration errors than controls during lexical and non-lexical reading.

Sequential same-different decision

The sequential same-different decision task consisted of 139 word pairs and 139 consonant-string pairs³, which were four or five letters in length. Half of the items were the same (e.g., *beard-beard*; *bfgsk-bfgsk*), and half were different (*beard-bread*; *bfgsk-bfsgk*). Half of the items in the different condition were different via the transposition of internal letters (e.g., *trial-trail*), and half were different via the substitution of a single letter (e.g., *chuck-check*). Items were included in both the same and the different condition (i.e., participants made responses to both *trial-trail* and *trial-trial*). Six versions of the task were created and presented over two sessions, such that participants only saw one version of the item (either in the same or in the different condition) in a single session. These 280 items were intermixed with an additional 280 items (half same, half different), which were not used to address the research questions in the present study.

Same-different decision trials were presented using DMDX software (Forster and Forster, 2003). A schematic of a single trial is outlined in Figure 2. The first item was both backwards masked and presented in a different case to the second item to ensure that participants could not match the items based on low-level perceptual overlap. Participants were instructed to press a button with their right hand if they thought the two items were the same, and to press a button with their left hand if they thought the two items were different. Participants were given eight practice trials before commencing the task. No performance-based feedback was given to participants at any stage during the task.

As LPDs have been found to have intact letter identification skills (Friedmann and Rahamim, 2007; Kohnen et al., 2012), the

³The task was designed to have 140 word pairs and 140 consonant-string pairs. However, one word pair in the same migration condition (e.g., *slime-slime*) and one consonant-string pair in the different migration condition (e.g., *dktlp-dltkp*) were removed from the analysis as they were not presented correctly.

Table 3 | Percentage of migration errors, single-substitution (sub) errors and double-substitution (sub) errors on the visual lexical decision task.

	LM	EL	LM and EL controls	LL	LL controls
Migration errors	64.29*	53.33*	24.89 (10.16)	43.75*	12.58 (9.82)
Single-sub errors	33.33*	8.33	6.94 (9.74)	8.33	3.33 (4.56)
Double-sub errors	25.00**	8.33	2.90 (4.51)	0.00	3.33 (7.45)

Numbers in parentheses denote standard deviation of the mean for control groups.

* $p < 0.05$, ** $p < 0.01$ compared to control group.

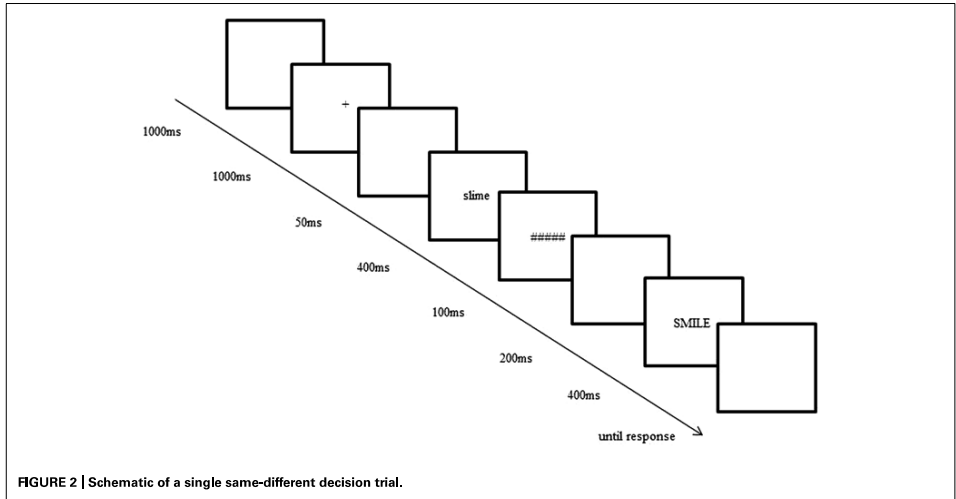


FIGURE 2 | Schematic of a single same-different decision trial.

substitution condition was used as an indication of baseline performance on the task. If LPD is due to an orthographic-visual analysis deficit, LPDs should be poorer than controls at detecting a difference between two migratable items (e.g., *slime-smile*), relative to the baseline condition (e.g., *tiger-timer*).

Table 4 displays participants' accuracy on the different conditions (i.e., their ability to detect that two items are different). Participants' d' scores based on their hits (correctly responding "different" to two different items e.g., *slime-smile*) and false alarms (incorrectly responding "different" to two same items e.g., *slime-slime*) on the migration and substitution condition are also included in **Table 4**.

All statistical analyses for the task were based on participants' accuracy on the different migration condition relative to their accuracy on the different substitution condition, using the Revised Standardized Difference Test (RSDT: Crawford and Garthwaite, 2005). All three LPDs were significantly poorer than controls at detecting that two migratable words were different relative to the substitution condition, however this only reached significance for EL and LL (EL: $t = 4.68$, $p = 0.003$ one-tailed; LL: $t = 2.82$, $p = 0.02$ one-tailed; LM: $t = 1.74$, $p = 0.07$). All three LPDs were not significantly poorer than controls at detecting that

two migratable consonant strings were different, relative to the substitution condition (all $t < 1.10$, $p > 0.16$).

The finding that all three LPDs were no poorer than controls at detecting a difference between two migratable consonant-strings seems inconsistent with an orthographic-visual analysis deficit account of LPD. If LPD is caused by an orthographic-visual analysis deficit, then LM, EL and LL should be poorer than controls at detecting a difference between two migratable items, regardless of their lexicality.

However, this result may have been due to participants not having enough time to process the entire consonant-string. Letters in words are thought to be processed in parallel as a single unit of information. In contrast, there is no higher-order representation for consonant strings, and therefore each letter needs to be processed serially as its own unit of information. The limited stimulus presentation time in the task (400 ms) may have therefore meant that children only had enough time to process the beginning letters of the items in the consonant-string condition. If only the beginning letters are processed, then a correct response to many of the items in the different migration condition would require intact letter identification skills, but not necessarily intact letter position coding skills. For example, if participants

Table 4 | Percentage accuracy for the different migration (mig) and substitution (sub) conditions on the same-different decision task, and d' scores.

		LM		EL		LM and EL controls		LL		LL controls	
		Accuracy	d'	Accuracy	d'	Accuracy	d'	Accuracy	d'	Accuracy	d'
Words	Mig	40.00	1.22	54.29	1.00	89.52 (6.68)	3.03 (0.68)	71.43	1.83	94.29 (5.35)	3.69 (0.59)
	Sub	80.00	3.01	100.00	3.35	93.81 (2.81)	3.25 (0.45)	91.43	2.60	96.00 (8.94)	3.85 (0.99)
Consonants	Mig	41.18	1.08	67.65	0.34	65.69 (8.86)	0.73 (0.53)	85.29	0.61	74.71 (25.01)	1.66 (1.08)
	Sub	22.86	0.43	80.00	0.78	60.00 (15.65)	1.16 (0.45)	65.71	0.29	73.71 (15.31)	1.68 (0.78)
Non-words	Mig	58.33	1.67	54.17	0.96	88.54 (9.85)	3.24 (0.77)	66.67	1.35	88.33 (11.56)	2.83 (0.99)
	Sub	70.83	1.99	100.00	2.92	96.88 (6.25)	3.85 (0.78)	87.50	2.02	95.83 (5.10)	3.22 (0.75)

Numbers in parentheses denote standard deviation of the mean for control groups.

are presented with the consonant–string pair *stlkd-sklt*, but they only have enough time to process the first three letters of the consonant string, *stl-sk*, participants need only detect that the letter identities *t* and *k* are different from one another to make a correct response. If participants were only processing the beginning letters of the consonant–string pairs, then the finding that LPDs did not make more errors on the migration condition is not surprising, as LPDs have been found to have intact letter identification abilities (Friedmann and Rahamim, 2007; Kohnen et al., 2012).

One way to investigate whether or not participants had enough time to process all letters in the consonant–string condition is to see whether there is a position effect. If participants did not have enough time to process the entire consonant–string, we should find that they are better at detecting a difference between two consonant strings if the letters are different at the beginning of the pair, than if the letters are different at the end of the pair.

In a *post hoc* analysis, we explored whether there was merit in this alternative hypothesis. Items that differed via the substitution of a single letter in the first internal position of the word (e.g., *nkdcg-njdcg*) were classified as having a “beginning difference,” and items that differed via the substitution of a single letter in the final internal position of the word (e.g., *fkzgd-fkmt*) were classified as having an “end difference.” The substitution condition rather than the migration condition was used because many of the different migratable items had both a beginning and end difference (e.g., *xtkjd-xjkt*).

All participants were combined to form one group for this item analysis. We used a Wilcoxon matched pairs test to compare the proportion correct on the two groups of items. Participants identified significantly more beginning differences (74.60%) in the consonant–string condition than end differences (58.574%; $z = 2.51$, $p = 0.006$ one-tailed). In contrast, participants identified as many beginning differences (93.57%) in the word condition as end differences (94.76%; $z = 0.51$, $p = 0.304$ one-tailed).

Following this finding, we decided to administer a same-different decision task with orthographically legal non-words (e.g., *scirm-scrim*). While the letters in legal non-words are not thought to be processed in parallel like words, the letters can be mapped onto a higher-order representation. For example, the consecutive letters *i* and *r* in the non-word *scirm* can be mapped onto the digraph *ir*. That is, the letters in legal non-words can be “chunked”

(*s*, *c*, *ir* and *m*) and, for this reason, are likely to be processed faster than consonant–strings which cannot be chunked.

The non-word same-different decision task consisted of 96 non-word pairs. Forty-eight of the pairs were in the same condition, and 48 were in the different condition. Half of the items in the different condition were different via the transposition of two internal letters (e.g., *scirm-scrim*), and half were different via the substitution of a single letter (e.g., *froy-floy*). The same condition consisted of 48 non-word pairs. In contrast to the word and consonant string same-different decision task, non-words in the same condition were a new set of items, not derived from the items in the different condition (i.e., participants did not see *scirm-scrim* and *scirm-scrim*). Non-words were presented to participants during a single task, and under the same presentation conditions as described for the words and consonant–strings task.

By the time we assessed LM and EL on this task they were in the second semester of grade 5. Therefore, we compared their performance on this task to a new control group of 4 children in their second semester of grade 5.

Table 4 displays participants’ accuracy on the different conditions. Participants’ d' scores based on their hits (correctly responding “different” to two different items e.g., *scirm-scrim*) and false alarms (incorrectly responding “different” to two same items e.g., *garp-garp*) on each condition are also included in Table 4. False alarms were calculated from participants’ performance on all 48 items in the same condition.

EL was significantly poorer than controls at detecting when two migratable non-words were different relative to the substitution condition (EL: $t = 4.47$, $p = 0.01$ one-tailed). LM and LL, however, did not show this effect (both $t < 1.64$, $p > 0.10$). We assessed for a position effect in the same way as we did for the consonant–string and word items. Participants correctly identified as many beginning differences (95.14%) as end differences (91.67%; $z = 0.54$, $p = 0.30$ one-tailed), indicating that they had enough time to process the entire letter string.

The finding that all three LPDs made more word migration errors than controls on a sequential same-different decision task is consistent with an orthographic-visual analysis deficit account of LPD, as is the finding that EL made more non-word migration errors on the task. The finding that LM and LL did not make

more non-word migration errors on the sequential same-different decision task is, however, inconsistent with an orthographic-visual analysis deficit and will be followed up in the discussion.

Reading aloud non-words. Non-words were created from 25 non-word pairs which were migratable via the transposition of two internal adjacent letters (e.g., *torm-trom*). Pairs were selected to have a significant difference in bigram frequency between the two non-words (lower bigram frequency counterpart: $M = 789.56$, $SD = 594.36$; higher bigram frequency counterpart: $M = 1389.80$, $SD = 841.41$). Non-words were selected to match their migration partner as closely as possible on substitution N (lower bigram frequency counterpart: $M = 2.44$, $SD = 2.38$; higher bigram frequency counterpart: $M = 3.00$, $SD = 2.65$). Non-words were randomized and intermixed with 25 additional monosyllabic non-words that were not used to answer the research questions in this paper. Three versions of the task were created such that participants did not see a non-word and its migration partner in the same task. Participants were told that all items were nonwords before commencing the task.

The results from the nonword reading task are presented in Table 5. Both LM and LL made significantly more non-word migration errors on the task than controls (LM: $t = 6.46$, $p < 0.001$ one-tailed; LL: $t = 2.96$, $p = 0.02$ one-tailed) and made as many non-migration related errors as controls (LM: $t = 0.04$, $p = 0.48$ one-tailed; LL: $t = 1.82$, $p = 0.07$ one-tailed). EL did not make more nonword migration errors than controls ($t = 0.18$, $p = 0.43$ one-tailed) and made more non-migration related errors than controls ($t = 2.95$, $p = 0.02$ one-tailed).

Following the finding that EL showed the opposite effect to that displayed by LM and LL (i.e., as many migration errors as controls, but more non-migration related errors than controls), we decided to inspect EL's non-word reading data more closely. We found that 23% of EL's non-migration errors were what we have termed, "over-sequential" errors. An "over-sequential" error was defined as an error that appeared likely to have occurred as a result of sounding out each letter in the non-word in isolation, and then blending these sounds together to form a spoken response. For example, EL read *kerm* as /k /ε/ /r/ /m/. That is, instead of reading the letters *e* and *r* together to correctly form the sound /εr/, he sounded out these two letters separately. For two of these errors, EL first misread

the non-word as its migration partner, and then self-corrected with an over-sequential error. Furthermore, for all but one of EL's over-sequential errors, EL demonstrated that he knew the sound associated with the multi-letter grapheme he over-sequentialized by correctly producing it on at least two other items within the list. EL's control group did not make a single "over-sequential" error on this task. This finding suggests that EL's limited migration errors on this task (compared to the other LPDs in the study) may have been the result of him sounding out each letter in isolation of the other letters within the word.

The findings from the reading aloud non-words task suggest that LPD is most likely caused by an orthographic-visual analysis deficit. However, there appears to be variation in task performance among the three LPDs in the present study.

Item variables influencing non-word migration errors. In the present study, we also explored the possibility that there may be specific item variables that influence whether or not LPDs will make non-word migration errors. Specifically, we explored whether the bigram frequency of the non-word migration counterpart relative to the bigram frequency of the non-word itself, influenced whether or not a non-word migration error will be made.

We investigated the influence of bigram frequency on non-word reading by analyzing the migration errors made by LM and LL. Specifically, we compared the number of migration errors made on the lower bigram frequency partner ($N = 25$) to the number of migration errors made on the higher bigram frequency partner ($N = 25$). The other participants' results (EL and both control groups) were not investigated in this additional analysis as they made very few migration errors on the task. Both LM and LL read as many non-words as their higher bigram frequency migration partner (LM: 40%; LL: 8%) as they did non-words as their lower bigram frequency partner (LM: 40%; LL: 24%; both Fisher's exact $p > 0.12$ one-tailed).

While bigram frequency was not found to mediate migration errors on this task, a *post hoc* analysis revealed that LM and LL's migration errors were influenced by the complexity of the graphemes that made up each non-word. LM and LL were more likely to migrate a two-letter grapheme into two single-letter graphemes (e.g., reading *kerm* as "krem") than to migrate two single-letter graphemes into a two-letter grapheme (e.g., reading *krem* as "kerm"). Both LM and LL were found to migrate significantly more two-letter graphemes into single letter graphemes (LM: 66.67%, LL: 33.33%) than two single-letter graphemes into a two letter grapheme (LM: 11.11%, LL: 0%, both Fisher's exact $p < 0.02$ two-tailed).

An examination of the order of item presentation was conducted to investigate whether the errors where a two-letter grapheme migrated into two single-letter graphemes were due to participants being primed by the two single-letter graphemes. That is, we examined whether participants saw the two single letter graphemes (e.g., *frempt*) prior to making an error where they migrated a two-letter grapheme into these two-single letters (e.g., reading *kerm* as *krem*). Of the 18 errors made by LM and LL where a two-letter grapheme was migrated into two single letters (e.g.,

Table 5 | Percentage of migration errors (mig error) and non-migration related errors (non-mig error) on reading aloud non-words.

	LM	EL	LM and EL controls	LL	LL controls
Mig error	40***	6	5.00 (5.02)	16*	4.40 (3.58)
Non-mig error	12	36*	12.33 (7.42)	20	7.20 (6.42)

Numbers in parentheses denote standard deviation of the mean for control groups.

* $p < 0.05$, *** $p < 0.001$ compared to control group.

where *kern* was read as “*krem*”), only three errors were made directly after having seen a non-word that comprised the same two single letters (e.g., *frempt*).

DISCUSSION

This study investigated the locus of impairment in three English-speaking children with developmental LPD. Previous research has used a cognitive model of reading aloud to identify three alternative processing components that may be the cause of LPD: the phonological output buffer, the orthographic input lexicon, and orthographic-visual analysis. First, we aimed to replicate previous findings that have ruled out a phonological output buffer deficit and an orthographic input lexicon deficit account of LPD. We then went on to extend previous findings that suggest LPD is caused by an orthographic-visual analysis deficit.

ASSESSING THE PHONOLOGICAL OUTPUT BUFFER

It is plausible to assume that the excessive migration errors made by LPDs are due to the phonemes in the phonological output buffer being swapped around before the word is pronounced. Together with previous studies, our findings strongly refute this hypothesis (Friedmann and Rahamim, 2007; Kohnen et al., 2012; see also Collis et al., 2013). All three LPDs in the present study were either within or above the average range on various standardized tests that draw heavily on a functioning phonological output buffer to be completed successfully. Furthermore, LPDs were asked to repeat a subset of the migratable words that they had previously made a migration error on in a reading aloud task. Each LPD performed this task without making a single migration error, indicating that their reading aloud errors were not caused by an inability to produce the word's phonemes in the correct order.

In recent years, various researchers have suggested that underlying dyslexia is a phonological processing deficit (Stanovich, 1988; Snowling, 1998, 2001; Ramus, 2003). The findings from the present study indicate that, while some children with reading difficulties have phonological processing difficulties, other children's reading difficulties are likely to reflect an alternative processing deficit. For example, surface dyslexia is most likely caused by an orthographic processing deficit (e.g., Castles and Coltheart, 1993, 1996; Broom and Doctor, 1995; Temple, 1997), attentional dyslexia is most likely caused by a letter-to-word binding deficit (Rayner et al., 1989; Friedmann et al., 2010b), and LPD is most likely caused by a letter position coding deficit (for more discussion of heterogeneity within developmental dyslexia, see Castles et al., 2010; Zoccolotti and Friedmann, 2010; McArthur et al., 2013).

ASSESSING THE ORTHOGRAPHIC INPUT LEXICON

It is also plausible to assume that the migration errors made by LM, EL and LL are the result of lexical guessing due to an impoverished orthographic input lexicon. The finding that all three LPDs read aloud non-migratable irregular words as well as controls indicates that this is not the case. Furthermore, EL and LL made more migration errors than controls during a reading aloud task and a visual lexical decision task but did not make more substitution and *N* errors than controls. These findings indicate that EL and LL's errors on these tasks were specific to the migration of letters within the word and were therefore not due to lexical guessing.

In contrast to EL and LL, LM made more migration errors than controls on the visual lexical decision task and more substitution errors on the task. This finding suggests that perhaps LM's tendency to make excessive migration errors is the result of lexical guessing. While this finding does not fall in line with our predictions, we believe that LM's lexical guessing was confined to this task, and that her broader tendency to make more migration errors than her peers cannot be attributed to a lexical guessing strategy. If LM's excessive migration errors are the result of lexical guessing, then she should have been found to make more errors that are visually similar to the target word when reading aloud (e.g., reading *slime* as “slide” or “slim”) than controls. This was not the case. Like EL and LL, LM made more migration errors than controls when reading aloud, but the same amount of substitution and *N* errors.

ASSESSING THE ORTHOGRAPHIC-VISUAL ANALYSIS STAGE OF READING

The first aim of the present study was to replicate the finding that LPD cannot be attributed to a phonological output buffer deficit or an orthographic input lexicon deficit. Our findings converge with previous research that has ruled out these two possible loci as the source of migration errors seen in LPD (Friedmann and Rahamim, 2007; Kohnen et al., 2012). Having addressed our first aim, we now turn to a discussion of our second aim: to extend the investigation of a possible orthographic-visual analysis deficit account of LPD.

The present study extended Kohnen et al.'s (2012) study in three ways: (1) administering a sequential same-different decision task, (2) administering consonant-strings and orthographically legal non-words in the sequential same-different decision task, and (3) manipulating bigram frequency in a non-word reading task. We hoped that making these changes would provide us with tasks that were more sensitive to an orthographic-visual analysis deficit, and hence enable us to draw stronger conclusions regarding the locus of impairment in English LPD.

In the present study, we administered a sequential same-different decision task to ensure that participants would be unable to adopt a strategy whereby they compare each letter in the pair to one another. We found that EL and LL made significantly more word migration errors on the task than controls. LM also showed this trend, however it did not reach significance. One key difference between the present study and Kohnen et al.'s (2012) study was EL's performance on the same-different decision task. While EL did not make more migration errors on Kohnen et al.'s (2012) simultaneous same-different decision task, he made significantly more migration errors on a sequential variant of the task in the present study. One interpretation of this finding is that EL was adopting a letter-by-letter matching strategy during Kohnen et al.'s (2012) simultaneous same-different decision task. When he was unable to adopt this strategy during the present study, due to the sequential presentation of words, he made significantly more migration errors than controls.

An alternative interpretation of EL's excessive migration errors on the same-different matching task in the present study is that a sequential variant of the task encourages participants to convert the word into a phonological form due to the limited presentation

time of the items. It might therefore be that EL made excessive migration errors on the sequential task because he compared the words in each pair based on phonological form, whereas in Kohnen et al.'s (2012) simultaneous task, words were compared based on their orthographic form. We believe this alternative hypothesis to be unlikely for two reasons. Firstly, a wealth of research has shown that responses made on a same-different decision task are based on prelexical orthographic representations rather than phonological representations (e.g., Besner et al., 1984; Kinoshita and Norris, 2009). Secondly, EL was found to be within (or above) the average range on tests that assess phonological processing. It is therefore highly unlikely that EL's excessive migration errors on the sequential same-different decision task could be reflecting a difficulty in comparing phonological forms.

A consonant-string condition in the same-different decision task was included in the present study under the assumption that a letter position coding deficit should manifest itself in responses to all letter-strings, regardless of lexicality. Contrary to our prediction, LPDs did not make more migration errors than controls on the consonant-string condition. We believe that this finding was due to the different mechanisms underlying the processing of letters in words and in consonant-strings. While letters in words are thought to be processed in parallel as a single unit, each letter in a consonant-string needs to be processed serially as a single unit. This means that letters in consonant-strings are likely to take longer to process than letters in words. The *post hoc* finding that participants were significantly better at identifying a difference between two consonant strings when the difference occurred toward the beginning of the consonant pair (*fkztzm-ftlzm*) than when the difference occurred toward the end of the consonant pair (*fkztzm-fklzm*) suggests that 400ms was not enough time for participants to process the entire consonant-string. For this reason, we believe that participants' performance on the consonant-string condition cannot be taken as evidence for or against an orthographic-visual analysis deficit account of LPD.

Following this finding, we conducted a sequential same-different decision task with orthographically legal non-words. We found that while EL made significantly more migration errors than controls on this task, LM and LL did not. The finding that EL made more word and non-word migration errors on a same-different decision task strongly suggests that EL's excessive migration errors are caused by an orthographic-visual analysis deficit. In contrast, the finding that LM and LL made more migration errors on the word condition, but not on the non-word condition is not predicted by an orthographic-visual analysis deficit account of LPD. Rather, LM and LL should have been found to make more migration errors on a sequential same-different decision task, regardless of the lexicality of the items. However, LM and LL's data are still most consistent overall with an orthographic-visual analysis deficit. Further investigations may need to focus on the interaction between lexicality effects and orthographic-visual analysis deficits in LPD.

We also administered a non-word reading task in the present study. If LPD is caused by an orthographic-visual analysis deficit, we should find that LPDs not only make more word migration errors (e.g., reading *slime* as "smile") than controls, but also more

non-word migration errors (e.g., reading *pilf* as "plif"), as a deficit at the orthographic-visual analysis stage of reading should impede both lexical and non-lexical reading. In the present study, we found that LM and LL made more non-word migration errors (e.g., reading *pilf* as "plif") than controls. This finding is in contrast with Kohnen et al.'s (2012) finding that all three LPDs made as many non-word migration errors as controls. Interestingly, the one LPD in the present study who did not make excessive non-word migration errors (EL) was one of the three LPDs in Kohnen et al.'s (2012) study who did not make excessive non-word migration errors when reading aloud. This finding is consistent with research in Hebrew that has found that while some LPDs make non-word migration errors, others do not (Friedmann and Rahamim, 2007). EL's over-sequential errors (where each letter was sounded out in isolation and then blended together to form a response) in the present study suggest that individual differences in strategy use might be one predictor of whether or not LPDs will make non-word migration errors.

Contrary to our exploratory hypothesis, we found non-word bigram frequency to have no influence over whether or not a migration error was made. That is, LM and LL were no more likely to read a non-word as its higher bigram frequency partner than they were to read a non-word as its lower bigram frequency partner. The majority of migration errors made by LPDs occur when two adjacent letters in the middle of a word can migrate to form a new word. Considering it is the internal letters of the non-word that are most prone to migration, it is perhaps not surprising that the bigram frequency of the entire letter-string (external letters included) did not influence whether or not a migration error occurred. Instead, it may be other factors specific to the letters that are most susceptible to migration that influence whether or not a migration error will be made.

This suggestion was supported by the *post hoc* finding that the complexity of the non-word's internal grapheme/s influenced whether or not a migration error was made. We found that LM and LL were more likely to swap the letters in a two-letter grapheme around to form two single-letter graphemes, than to swap two single letters around to form a two-letter grapheme (i.e., *kerm* was read as "krem" more than *krem* read as "kerm")⁴. One plausible explanation for this finding is that children are likely to be introduced to the sounds that the letters of the alphabet make (single-letter graphemes) before they are introduced to the sounds that two letters of the alphabet make together (two-letter graphemes). What this finding might therefore reflect is an age of acquisition effect. When the non-lexical route is provided with ambiguous letter position information, the default may be to resort to the letter-sounds that were first learnt. Future studies may seek to further our *post hoc* finding by directly testing the hypothesis that some graphemes may be more susceptible to migration than others.

⁴Note that following this finding we also analysed the influence of internal bigram frequency on migration errors using Solso and Juel's (1980) bigram frequency count database. That is, we analyzed whether or not LM and LL were more likely to migrate the lower frequency bigram *li* in the non-word *plim* into the higher frequency bigram *il* (resulting in the misreading of the non-word as "piln"). We found no influence of internal bigram frequency on LM and LL's migration errors.

CONCLUSION

The aim of this multiple single case study was to both replicate and extend previous findings regarding the locus of impairment in English LPD. Our findings converge with previous research by strongly suggesting that LPD cannot be attributed to a phonological output buffer or orthographic input lexicon deficit. Rather, our results suggest that LPD is most likely caused by a deficit specific to the coding of letter position at the orthographic-visual analysis stage of reading.

In line with previous studies, however, there was some variability in performance amongst the three children on the tasks designed to explicitly assess for an orthographic-visual analysis deficit. One thing that is becoming increasingly clear as research on LPD progresses is that localizing the source of the migration errors seen in LPD is no easy feat. While identifying what *does not cause* migration errors (i.e., a phonological output or orthographic input lexicon deficit) is relatively straightforward, identifying what *causes* migration errors is not as clear-cut. The findings from the present study suggest that variations in the manifestation of an orthographic-visual analysis deficit may be, at least in part, due to individual differences in strategy use. Therefore, to maximize the potential of localizing the deficit underpinning LPD, future research needs to ensure that the tasks used either eliminate or greatly reduce the opportunity for compensatory strategies to be adopted.

Finally, the finding that the three children in the present study were found to have great difficulty in reading migratable words, in the absence of any other obvious reading or spoken language difficulty, attests to the heterogeneity of dyslexia and its underlying causes. Our findings strongly suggest that not all children with reading difficulties have an impairment in phonological processing. Rather, our findings join a growing body of research in advocating the need to map this heterogeneity in developmental dyslexia, and to develop diagnostic tools that assess the variety of its underlying causes.

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REFERENCES

- Baayen, R. H., Piepenbrock, R., and Gulikers, L. (1995). *The CELEX Lexical Database (CD-ROM)*. Philadelphia, PA: Linguistic Data Consortium.
- Besner, D., Coltheart, M., and Davelaar, E. (1984). Basic processes in reading: computation of abstract letter identities. *Can. J. Psychol.* 38, 126–134. doi: 10.1037/h0080785
- Beyersmann, A. E., Duñabeitia, J. A., Carreiras, M., Coltheart, M., and Castles, A. (2013). Early morphological decomposition of suffixed words: masked priming evidence with transposed-letter nonword primes. *Appl. Psycholinguist.* 34, 869–892. doi: 10.1017/S0142716412000057
- Beyersmann, A. E., Castles, A., and Coltheart, M. (2011). Early morphological decomposition during visual word recognition: evidence from masked transposed-letter priming. *Psychon. Bull. Rev.* 18, 937–942. doi: 10.3758/s13423-011-0120-y
- Beyersmann, A. E., Coltheart, M., and Castles, A. (2012). Parallel processing of whole-words and morphemes in visual word recognition. *Q. J. Exp. Psychol.* 65, 1306–1326. doi: 10.1080/17470218.2012.656661
- Broom, Y. M., and Doctor, E. A. (1995). Developmental surface dyslexia: a case study of the efficacy of a remediation programme. *Cogn. Neuropsychol.* 12, 69–110. doi: 10.1080/02643299508251992
- Castles, A., and Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition* 47, 149–180. doi: 10.1016/0010-0277(93)90003-E
- Castles, A., and Coltheart, M. (1996). Cognitive correlates of developmental surface dyslexia: a single case study. *Cogn. Neuropsychol.* 13, 25–50. doi: 10.1080/026432996382051
- Castles, A., Coltheart, M., Larsen, L., Jones, K., Saunders, S., and McArthur, G. (2009). Assessing the basic components of reading: a revision of the Castles and Coltheart test with new norms. *Aust. J. Learn. Difficult.* 14, 67–88. doi: 10.1080/19404150902783435
- Castles, A., Coltheart, M., Wilson, K., Valpied, J., and Wedgwood, J. (2009). The genesis of reading ability: what helps children learn letter-sound correspondences? *J. Exp. Child Psychol.* 104, 68–88. doi: 10.1016/j.jecp.2008.12.003
- Castles, A., McLean, G. M. T., and McArthur, G. (2010). Dyslexia (neuropsychological). *Wiley Interdiscip. Rev. Cogn. Sci.* 1, 426–432. doi: 10.1002/wcs.16
- Collis, N. L., Kohnen, S., and Kinoshita, S. (2013). The role of visual spatial attention in adult developmental dyslexia. *Q. J. Exp. Psychol.* 66, 245–260. doi: 10.1080/17470218.2012.705305
- Coltheart, M., Rastle, K., Perry, C., Langdon, R., and Ziegler, J. (2001). DRC: a dual route cascaded model of visual word recognition and reading aloud. *Psychol. Rev.* 108, 204–256. doi: 10.1037/0033-295X.108.1.204
- Crawford, J. R., and 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. 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
- Davis, C. J. (2005). N-Watch: a program for deriving neighbourhood size and other psycholinguistic statistics. *Behav. Res. Methods* 37, 65–70. doi: 10.3758/BF03206399
- Denckla, M. B., and Rudel, R. G. (1976). Rapid “automatized” naming (R.A.N): dyslexia differentiated from other learning disabilities. *Neuropsychologia* 14, 471–479. doi: 10.1016/0028-3932(76)90075-0
- Forster, K. I., and Forster, J. C. (2003). DMDX: a windows display program with millisecond accuracy. *Behav. Res. Methods Instrum. Comput.* 35, 116–124. doi: 10.3758/BF03195503
- Friedmann, N., and Gvion, A. (2001). Letter position dyslexia. *Cogn. Neuropsychol.* 18, 673–696. doi: 10.1080/02643290143000051
- Friedmann, N., and Haddad-Hanna, M. (2012). Letter position dyslexia in Arabic: from form to position. *Behav. Neuropsychol.* 25, 193–203. doi: 10.3233/BEN-2012-119004
- Friedmann, N., Dotan, D., and Rahamim, E. (2010a). Is the visual analyzer orthographic-specific? Reading words and numbers in letter position dyslexia. *Cortex* 46, 982–1004. doi: 10.1016/j.cortex.2009.08.007
- Friedmann, N., Kerbel, N., and Shvimer, L. (2010b). Developmental attentional dyslexia. *Cortex* 46, 1216–1237. doi: 10.1016/j.cortex.2010.06.012
- Friedmann, N., and Rahamim, E. (2007). Developmental letter position dyslexia. *J. Neuropsychol.* 1, 201–236. doi: 10.1348/174866407X204227
- Høien, T., Lundberg, L., Larsen, J. P., and Tønnessen, F. E. (1989). Profiles of reading related skills in dyslexic families. *Read. Writ.* 1, 381–392. doi: 10.1007/BF00386268
- Kinoshita, S., and Norris, D. (2009). Transposed-letter priming of prelexical orthographic representations. *J. Exp. Psychol. Learn.* 35, 1–18. doi: 10.1037/a0014277
- Kohnen, S., and Castles, A. (2013). Pirates at parties: letter position processing in developing readers. *J. Exp. Child Psychol.* 115, 91–107. doi: 10.1016/j.jecp.2012.08.011
- Kohnen, S., Marinus, E., Friedmann, N., Anandakumar, T., Castles, A., Nickels, L., et al. (2014). *The Letter Position Test (LetPos)*. Available at: www.motif.org.au

- Kohnen, S., Nickels, L., Castles, A., Friedmann, N., and McArthur, G. (2012). When 'slime' becomes 'smile': developmental letter position dyslexia in English. *Neuropsychologia* 50, 3681–3692. doi: 10.1016/j.neuropsychologia.2012.07.016
- Korkman, M., Kirk, U., and Kemp, S. (1998). *A Developmental Neuropsychological Assessment (NEPSY)*. San Antonio, TX: The Psychological Corporation.
- Mann, V. A., and Liberman, I. Y. (1984). Phonological awareness and verbal short-term memory. *J. Learn. Disabil.* 17, 592–599. doi: 10.1177/002221948401701005
- Mann, V. A., Liberman, I. Y., and Shankweiler, D. (1980). Children's memory for sentences and word strings in relation to reading ability. *Mem. Cogn.* 8, 329–335. doi: 10.3758/BF03198272
- McArthur, G., Eve, P. M., Jones, K., Banales, E., Kohnen, S., Anandakumar, T., et al. (2012). Phonics training for English speaking poor readers. *Cochrane Database. Syst. Rev.* 12, 1–104. doi: 10.1002/14651858.CD009115.pub2
- McArthur, G., Kohnen, S., Larsen, L., Jones, K., Anandakumar, T., Banales, E., et al. (2013). Getting to grips with the heterogeneity of developmental dyslexia. *Cogn. Neuropsychol.* 30, 1–24. doi: 10.1080/02643294.2013.784192
- Perea, M., and Fraga, I. (2006). Transposed-letter and laterality effects in lexical decision. *Brain Lang.* 97, 102–109. doi: 10.1016/j.bandl.2005.08.004
- Perea, M. L., and Lupker, S. J. (2004). Can CANISO activate CASINO? Transposed-letter similarity effects with nonadjacent letter positions. *J. Mem. Lang.* 51, 231–246. doi: 10.1016/j.jml.2004.05.005
- Ramus, F. (2003). Developmental dyslexia: specific phonological deficit or general sensorimotor dysfunction? *Curr. Opin. Neurobiol.* 13, 212–218. doi: 10.1016/S0959-4388(03)00035-7
- Rastle, K., and Coltheart, M. (1998). Whammies and double whammies: the effect of length on nonword reading. *Psychon. Bull. Rev.* 5, 277–282. doi: 10.3758/BF03212951
- Rayner, K., Murphy, L. A., Henderson, J. M., and Pollatsek, A. (1989). Selective attentional dyslexia. *Cogn. Neuropsychol.* 6, 357–378. doi: 10.1080/02643298908253288
- Snowling, M. (1998). Dyslexia as a phonological deficit: evidence and implications. *Child Adolesc. Mental Health* 3, 4–11. doi: 10.1111/1475-3588.00201
- Snowling, M. (2001). From language to reading and dyslexia. *Dyslexia* 7, 37–46. doi: 10.1002/dys.185
- Solso, R. L., and Juel, C. L. (1980). Instrumentation and techniques: positional frequency and versatility of bigrams for two- through nine-letter English words. *Behav. Res. Methods Instrument.* 12, 297–343. doi: 10.3758/BF03201669
- Stanovich, K. E. (1988). Explaining the differences between dyslexia and the garden-variety poor reader. The phonological-core variable-difference model. *J. Learn. Disabil.* 21, 590–604. doi: 10.1177/002221948802101003
- Temple, C. (1997). *Developmental Cognitive Neuropsychology*. Hove: Psychology Press.
- Wagner, R., Torgesen, J., and Rashotte, C. (1999). *Comprehensive Test of Phonological Processing (CTOPP)*. Austin, TX: PRO-ED.
- Wechsler, D. (2003). *Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV)*. San Antonio, TX: The Psychological Corporation.
- Zoccolotti, P., and Friedmann, N. (2010). From dyslexia to dyslexias, from dysgraphia to dysgraphias, from a cause to causes: a look at current research on developmental dyslexia and dysgraphia. *Cortex* 46, 1211–1215. doi: 10.1016/j.cortex.2010.09.003

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Ethics Approval



MACQUARIE
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Yvette Kezilas <yvette.kezilas@mq.edu.au>

ARE: HS Ethics Application - Approved (5201200947)(Condition met)

5 messages

Fhs Ethics <fhs.ethics@mq.edu.au>

Wed, Mar 6, 2013 at 2:23 PM

To: Dr Saskia Kohnen <saskia.kohnen@mq.edu.au>

Cc: Professor Anne Castles <anne.castles@mq.edu.au>, Miss Yvette Kezilas <yvette.kezilas@mq.edu.au>, Dr Meredith McKague <mckaguem@unimelb.edu.au>

Dear Dr Kohnen,

Re: "Letter position coding in developing English readers"(5201200947)

Thank you for your recent correspondence. Your response has addressed the issues raised by the Faculty of Human Sciences Human Research Ethics Sub-Committee and you may now commence your research.

This research meets the requirements of the National Statement on Ethical Conduct in Human Research (2007). The National Statement is available at the following web site:

http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/e72.pdf.

The following personnel are authorised to conduct this research:

Dr Meredith McKague
Dr Saskia Kohnen
Miss Yvette Kezilas
Prof Anne Castles

Please note the following standard requirements of approval:

1. The approval of this project is conditional upon your continuing compliance with the National Statement on Ethical Conduct in Human Research (2007).
2. Approval will be for a period of five (5) years subject to the provision of annual reports.

Progress Report 1 Due: 6th March 2014
Progress Report 2 Due: 6th March 2015
Progress Report 3 Due: 6th March 2016
Progress Report 4 Due: 6th March 2017
Final Report Due: 6th March 2018

NB. If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. If the project has been discontinued or not commenced for any reason, you are also required to submit a Final Report for the project.

Progress reports and Final Reports are available at the following website:
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3. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final

Report and submit a new application for the project. (The five year limit on renewal of approvals allows the Sub-Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

4. All amendments to the project must be reviewed and approved by the Sub-Committee before implementation. Please complete and submit a Request for Amendment Form available at the following website:

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5. Please notify the Sub-Committee immediately in the event of any adverse effects on participants or of any unforeseen events that affect the continued ethical acceptability of the project.

6. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University. This information is available at the following websites:

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If you will be applying for or have applied for internal or external funding for the above project it is your responsibility to provide the Macquarie University's Research Grants Management Assistant with a copy of this email as soon as possible. Internal and External funding agencies will not be informed that you have final approval for your project and funds will not be released until the Research Grants Management Assistant has received a copy of this email.

If you need to provide a hard copy letter of Final Approval to an external organisation as evidence that you have Final Approval, please do not hesitate to contact the Ethics Secretariat at the address below.

Please retain a copy of this email as this is your official notification of final ethics approval.

Yours sincerely,

Dr Peter Roger
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