THE COMPARATIVE MECHANISMS OF SILENT READING AND READING ALOUD IN PEOPLE WITH DYSLEXIA

by

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ABSTRACT

Developmental dyslexia is a lifelong condition that manifests itself as a reading and spelling impairment. This thesis explored the quality of lexical representation in the neurotypical and dyslexic populations, using a suite of individual difference measures and the masked priming paradigm. Chapters 2 and 3 revealed that in the neurotypical population, the priming effect in word recognition was driven by a component related to phonological precision, while a factor linked to orthographic precision contributed to the priming effects of word and pseudoword production. Chapter 4, demonstrated in the dyslexic population, the priming effects in word and pseudoword rejection was driven by a component linked to lexical precision, whereas no individual factor drove the priming effects for word or pseudoword production. Chapter 5 showed that that 34% of people with dyslexia had stuttered during childhood, with the prevalence rate being moderated by the severity of dyslexia. In addition, people with dyslexia did not differ from people who stutter in any phonological processing measures. These findings indicate that people with dyslexia have a phonological, together with orthographic precision, impairment.

Keywords: dyslexia, word recognition, word production, neurotypical, lexical quality

~For all PhD students that never finished or never had the opportunity to start ~

~For my Cat~

Leo (R.I.P)

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CHAPTER 1

GENERAL INTRODUCTION

INTRODUCTION

Language is a uniquely human ability. Most humans can naturally acquire a spoken language without explicit instruction. However, reading written language cannot be acquired in the same way as speech. People learn to read through instruction. However, despite adequate schooling, some people are unable to achieve the adequate reading level expected for their age and general intelligence. Developmental dyslexia manifests itself as the inability to acquire age-appropriate reading and spelling skills. Research has shown that children with dyslexia (CWD) have poorly specified phonological representations (see reviews by Bishop & Snowling, 2004; Hulme & Snowling, 2013). It is agreed that across languages, people with dyslexia (PWD) have a phonological deficit (Ziegler & Goswami, 2005). However, PWD have an additional difficulty in orthographic processing, demonstrated in poor spelling ability, and to some extent, semantic processing, as shown in poor reading comprehension (see review by Bishop & Snowling, 2004; Ransby & Swanson, 2003). This highlights that phonology alone cannot explain the pathogenesis of dyslexia and that phonological, orthographic and semantic impairment may be subsumed under a poor lexical representation. One of the aims of this thesis is to investigate the factors underlying the dyslexia diagnosis.

According to the Lexical Quality Hypothesis (LQH; Perfetti, 2007, 2017; Perfetti & Hart, 2002), PWD and poor readers struggle with decoding (i.e. spelling-sound relationships to read a word; Katz et al., 2012), as it is a slow and effortful process that depletes cognitive resources. These resources are therefore not available for other processes, such as lexical access and articulation, leading to a slowing down of word reading and naming. In addition, it has also been claimed that PWD have poorly specified phonological and orthographic representations and struggle to discriminate the target amongst its phonological neighbours (Elbro, 1996, 1998; Perfetti, 2007). The resources for PWD are therefore dedicated to the lower-level processes of reading, which negatively affects higher-level processes such as access to lexical-semantics. In contrast to PWD, more skilled readers are thought to have more precise and fully specified lexical representations that have redundant links between orthographic and phonological features (Perfetti, 2007, 2017). In turn, skilled readers are able to directly access the representation of a word and are proficient at suppressing its neighbours. This frees up resources for higher-level mechanisms such as semantics.

This thesis assesses the LQH in word production and recognition in a neurotypical and a dyslexic population. Research has demonstrated that underlying traits of dyslexia (e.g. poor phonological working memory, spelling and reading fluency) are linked to poorer performance in word production and recognition (e.g. Andrews & Hersch, 2010; Aguilar-Vafaie, Safarpour, Khosrojavid, & Afruz, 2012; Badian, 2005; Shapiro, Carroll & Solity, 2013). Such traits also vary in the neurotypical population, but it remains unclear to what extent these traits produce the same effect in the two populations, as orthography, phonology and semantics are rarely measured together, with the same participants, tasks and stimuli. There is a dearth of research examining how the traits that are implicated in dyslexia affect word recognition and production in a neurotypical population. This thesis addresses this gap by conducting the first systematic investigation of word recognition and production in both neurotypical and dyslexic participants and link their performance to a suite of individual difference measures (i.e. orthography, phonology and semantics). The thesis primarily focuses on competition resolution (i.e. the ability to select the correct target, while suppressing the irrelevant neighbouring candidates; Bexkens, van den Wildenberg & Tijms, 2015). This process is fundamental for reading and for speech production and perceived as a central problem in dyslexia (e.g. Bexkens et al. 2015; see review by Perfetti, 2007). A series of studies is presented that uses the masked priming task in word recognition and production to assess how individual differences in neurotypical and dyslexic populations affect the behavioural abilities linked to word recognition and production. The results have implications for understanding the individual differences that underpin silent reading and reading aloud and have consequences for how dyslexia should be conceptualised in order to provide more effective interventions.

In addition, the findings for an articulatory difficulty in PWD may result from a speech production difficulty such as stuttering. Stuttering is a neurodevelopmental condition that results in difficulties to formulate motor plans for speech production (Guitar, 2013). At first glance dyslexia and stuttering are unrelated conditions, as the former is a reading difficulty and the latter is a speech difficulty, anecdotal evidence have shown that these two conditions may have higher co-occurrence rate than expected (Blood, Ridenour Jr, Qualls & Hammer, 2003; Orton, 1928). In addition, evidence has shown that childhood stuttering adversely affects long-term articulatory abilities, even if the child recovers from childhood stuttering, leading to weaker speech production (Chang, Erickson, Ambrose, Hasegawa-Johnson & Ludlow, 2008). The weaker speech production in PWS has been argued to result from a phonological deficit. Pelczarski (2011) assessed whether PWS have a poor phonological encoding impairment and found that PWS performed worse in phoneme elision and nonword repetition than the control population. These findings indicate that PWS and PWD might share a common underlying deficit, that is a phonological deficit. If such an overlap exists, then this could also advance interventions, both for PWD and PWS and may explain the weaker performance for reading aloud.

THESIS STRUCTURE

The thesis consists of six chapters: an introductory chapter (Chapter 1), four empirical chapters and a closing discussion chapter (Chapter 6). Each empirical chapter, excluding Chapter

4, has been written as a self-contained paper[1] and each starts with an in-depth overview of the relevant experimental and theoretical literature.

The first empirical chapter, Chapter 2, assesses how orthographic, phonological and semantic processes affect competition resolution in word recognition in a neurotypical population. In this study (and the others included in the thesis), these processes were measured using a suite of tasks in addition to the standardised tests used to assess dyslexia, namely the Comprehensive Test of Phonological Processing (CTOPP) and the Test of Word Reading Efficiency (TOWRE). Competition resolution during word reading was measured using a masked priming paradigm (Forster & Davis, 1984), wherein participants are presented with a written prime for 50ms, followed by a target stimulus to which a response needed to be made (either a lexical decision or naming). Primes were either orthographically related or unrelated to the targets, and primes and targets were either words (e.g.peep-PEEK, vile-PEEK, hail-HAID or luck-HAID) or pseudowords (e.g. peet-PEEK, vire-PEEK, hait-HAID and lusk-HAID). The accepted view (e.g. Davis & Lupker, 2006) is that during prime presentation, other form-related words (its neighbours) will receive activation. In the related condition, this includes the upcoming target word. These neighbours must be suppressed to enable prime recognition. As a consequence, when the prime and target are neighbours (i.e. related), reaction times to the target will be slowed due to the target having been suppressed during prime presentation. This task therefore assesses the speed of competition resolution during visual word recognition. Further evidence for this suppression comes from studies varying neighbourhood density (NHD, i.e. the number of neighbours). Word targets with dense neighbourhoods were more likely to show inhibitory priming (i.e. word targets preceded by related primes were responded to more slowly than word targets that followed unrelated primes;

[1] Although these theses are written as 1st person, the empirical chapters have been written in 1st person plural as they have been submitted or written in preparation for submission.

e.g. Davis & Lupker, 2006), whereas word targets with sparse neighbourhoods were more likely to demonstrate facilitatory priming (i.e. word targets preceded by related primes were responded to more quickly than word targets that followed unrelated primes; Davis & Lupker, 2006). Slower reaction times due to form-related primes can therefore be taken as an indicator of effective competition resolution and arguably good lexical precision (Andrews, 2012, Andrews & Hersch, 2010).

The masked form priming task was therefore chosen as it captures a critical component involved in word recognition and production that depends on efficient use of competition resolution, a core impairment in dyslexia (Bexkens et al., 2015). As stated, prior studies with neurotypical participants have yielded mixed findings for masked form priming for word targets with dense neighbourhoods (e.g. Andrews & Hersch, 2010; Davis & Lupker, 2006) with some participants showing facilitatory rather than inhibitory priming effects, suggesting that this measure is sensitive to individual differences in lexical precision (see review by Andrews, 2012; Andrews & Hersch, 2010; Perfetti, 2007). The current study revealed that the priming effect is modulated by phonological precision and NHD. Participants with high phonological precision showed inhibitory priming for word targets with dense neighbourhoods, but facilitatory priming was shown for target words with sparse neighbourhoods. Facilitatory priming was shown, irrespective of NHD, in participants with low phonological precision. These findings suggest that the component of phonological precision is linked to the inhibitory effects of lexical competition for word recognition.

The study reported in Chapter 3 investigates whether the findings shown for masked priming in the lexical decision task generalise to a pseudoword and word production task. This question is important, as production includes not only the same processes as the recognition task, but also other processes that are not included in recognition, such as phonological encoding (i.e. individual phonemes are chosen and incrementally assembled in preparation for speech; Pelczarski, 2011). To address this question, we used the same design as in Chapter 2, but the participants had to name the word or pseudoword. This study revealed, for the first time, that the priming effect in naming is modulated by orthographic precision, NHD and prime lexicality. Decreased facilitatory priming for target words with dense neighbourhoods was shown with increasing orthographic precision. For target words with sparse neighbourhoods preceded by pseudoword primes, there was a decreased facilitatory priming effect with increasing orthographic precision. The converse was demonstrated for target words with sparse neighbourhoods preceded by word primes. These finding differ in interesting ways to those for the lexical decision task (Chapter 2) and suggest that people with high orthographic precision rely more heavily on the lexical route than sublexical route, the opposite pattern is shown for people with low orthographic precision.

In Chapter 4 we turn to PWD, who struggle in word recognition and production (see reviews by Melby-Lervag, Lyster & Hulme, 2012; Snowling & Melby-Lervag, 2016). Using the same paradigms from Chapters 2 and 3 to assess pseudoword and word recognition and production in the control population, Chapter 4 investigates the effects of orthography, phonology and semantics for competition resolution in word recognition and production in PWD. The findings from this chapter are as follows: first, the priming effect for PWD was modulated by the component of lexical precision, NHD and prime lexicality. PWD who had low lexical precision showed little, if any, priming effects. However, PWD who had high lexical precision showed inhibitory priming for word targets with dense neighbourhoods and sparse neighbourhoods. Compared to the finding that phonological precision is related lexical competition in the neurotypical population, PWD have an intact lexical representation and lexical precision is related to lexical competition in the dyslexic population. The results also revealed that competition resolution in word naming was not affected by individual differences. Finally, only an interaction of relatedness and NHD was observed such that word targets with dense neighbourhoods showed smaller facilitatory priming than those with sparse neighbourhoods. In pseudoword naming, only a prime lexicality and relatedness interaction was demonstrated where participants showed larger facilitatory priming for pseudoword targets preceded by word primes than those following pseudoword primes. These finding suggest that orthographic precision is necessary to suppress competitors for visual word naming as shown in Chapter 2, but phonological decoding and orthographic precision are impaired in PWD that they never achieve precise and fully specified orthographic representations.

Finally, in Chapter 5, we therefore investigated the co-occurrence of dyslexia and childhood stuttering, using a demographic questionnaire and the educational reports of PWD. Specifically, this study assessed the differences between PWD and PWS with the same individual difference measures from Chapters 2 to 4. Findings from this chapter provided the following results: first, dyslexia co-occurred with childhood stuttering around 34% of the time and was moderated by the severity of dyslexia: 15% of people with mild dyslexia had stuttered during childhood, whereas 47% of people with severe dyslexia had stuttered during childhood. In addition, 50% of PWS matched the dyslexia profile. Second, PWD and PWS did not differ in phonological processing and reading fluency. These findings suggest PWS and PWD may share an underlying phonological impairment.

In closing, Chapter 6 summarises the findings of the thesis. The final chapter brings together the results from the empirical chapters and draws overarching conclusions relating to competition resolution in people with dyslexia and neurotypical population. In addition, I discuss research limitations and future research.

CHAPTER 2.

PHONOLOGICAL PRECISION FOR WORD RECOGNITION IN SKILLED READERS[2]

[2] This chapter is currently under review: Elsherif, Wheeldon, L.R., & Frisson, S. Phonological precision for word recognition in skilled readers.

ABSTRACT

This study investigated individual differences in the neighbourhood density effect observed during the processing of written words. A masked priming experiment measured form priming for word and pseudoword targets with dense and sparse neighbourhoods in 84 university students. In addition, individual difference measures of language and cognitive processes were collected, and a principal component analysis was used to group these data into factors. We observed facilitatory form priming for words with a sparse neighbourhood and inhibitory form priming for words with a dense neighbourhood. A factor relating to phonological precision was positively related to priming effects for word targets with sparse neighbourhoods, but negatively related to priming effects for word targets with dense neighbourhoods. These results suggest that the component of phonological precision is linked to the inhibitory effects of lexical competition for word recognition. The implications for theories of reading skills, such as the Lexical Quality Hypothesis, are discussed.

Keywords: Lexical Quality Hypothesis; Visual Word recognition; orthography; phonology; semantics

PUBLIC SIGNIFICANCE STATEMENT

The authors assessed the role of phonological precision (i.e. the ability to directly access the sounds of words) and orthographic precision (the ability to directly access the written form of a word) in visual word recognition. The results of the study showed that phonological precision influences the ability to suppress competition between words that are similar in pronunciation and writing. These findings help us better understand the role of phonology in visual word recognition in skilled adults.

INTRODUCTION

In the word recognition literature, evidence has accumulated that, during word reading, a target word's neighbours (i.e. words that differ from the target word by one letter or sound; Coltheart, Davelaar, Jonasson, & Besner, 1977; see review by Davis, 2003) become active. Competition between a word and its neighbours must therefore be resolved for a word to be recognised. Much of the evidence for this comes from the masked priming paradigm, wherein a prime word is briefly presented below conscious awareness, after which a response, often a lexical decision (i.e. decide whether a letter string is a word or not; LDT), is made to a target letter string (Forster & Davis, 1984). In this task, responses to word targets can be inhibited by the brief presentation of a form-related prime differing by one letter from the target word, consistent with competition between form-related words (e.g. wine-VINE; Andrews & Hersch, 2010; Davis & Lupker, 2006).

Furthermore, competition resolution has been found to be affected by a word's neighbourhood density (NHD; i.e. the number of neighbours). Facilitatory priming has been shown for words with sparse neighbourhoods (few neighbours; e.g. VEIL has only VEIN and VEAL), but not words with dense neighbourhoods (i.e. many neighbours; e.g. BEAR has BEER, GEAR, BEAT, BEAD, TEAR inter alia). This is also known as the *density constraint effect* (e.g. Forster & Taft, 1994; Perea & Rosa, 2000). Interestingly, the degree of form priming can also be modulated by individual differences. Andrews and Hersch (2010) found that poor spellers showed facilitatory priming, irrespective of NHD, whereas good spellers showed inhibitory priming for word targets with dense neighbourhoods and facilitatory priming for those with sparse neighbourhoods. It has been proposed that the *quality* of lexical representations modulates competition resolution such that readers with good lexical representations have better competition resolution as they can inhibit competitors more strongly whereas readers with poor lexical representations have poorer competition resolution as they inhibit competitors less strongly (Perfetti & Hart, 2001; 2002; cf.

the Lexical Quality Hypothesis, Perfetti, 2007). Put simply, having a precise whole-word representation increases the efficiency of visual word processing, whereas imprecise whole-word representations lead to noisy processing of visual words. However, few studies have examined which facets of lexical quality modulate lexical retrieval in competition resolution. To date only spelling (i.e. an orthographic measure; Andrews & Hersch, 2010; Andrews & Lo, 2012; Andrews & Lo, 2013; Andrews, Lo & Xiao, 2017), vocabulary and reading comprehension (i.e. a semantic measure; Andrews & Hersch, 2010; Andrews & Lo, 2012; Andrews & Lo, 2013; Andrews et al., 2017; Perfetti, 2007) have been used to assess individual differences in word recognition. The present study therefore assessed how NHD, measures of orthography, phonology and semantics influence lexical competition among neighbours in a masked priming paradigm.

The purpose of the present study is to investigate lexical quality effects on competition resolution during written word recognition. Our study comprises an experiment testing the masked priming of written words with dense and sparse neighbourhoods and a large suite of language and cognitive tasks in order to assess individual differences in lexical quality. In addition, in our masked priming experiment, we test both word and pseudoword primes and targets. Pseudowords lack a lexical representation, thus emphasising sublexical processes such as grapheme-phoneme conversion, as opposed to lexical competition. Manipulating prime-target lexicality can therefore assess the contribution of sublexical processes to competition resolution during word recognition (Davis & Lupker, 2006).

In the following sections, we first review the theories and methodological parameters of the masked priming paradigm, along with the evidence for the role of lexical tuning in masked priming. We then outline the Lexical Quality hypothesis (LQH) and its application to lexical precision. Finally, we discuss lexical precision concerning target lexicality.

Masked priming and competition resolution

Patterns of facilitation and inhibition in the masked priming task for word targets when preceded by neighbour primes have been shown to vary due to several factors. First, the strength of inhibitory priming depends on prime frequency. Primes that are more frequent than the target produce stronger inhibition than primes that are less frequent than the target (e.g. Segui & Grainger, 1990; see review by Grainger, 1992). A high-frequency word prime (e.g. bear) is processed more quickly than a low-frequency word prime and can therefore suppress its neighbours - including the target word (GEAR) – more strongly prior to target presentation (i.e. target neighbour suppression), resulting in inhibitory priming. In contrast, a low-frequency prime (e.g. gear) would become activated along with its neighbouring words – including the target word (e.g. BEAR) – but may fail to suppress its neighbours prior to target presentation. This can result in facilitatory priming (Andrews & Hersch, 2010; Segui & Grainger, 1990). This indicates that shared neighbourhoods for word primes and targets influence processing speed (e.g. Van Heuven, Dijkstra, Grainger, & Schriefers, 2001).

Second, different patterns of priming effects have been observed to be dependent on whether the prime is a word or pseudoword (i.e. a pronounceable nonword). As stated, word primes can lead to inhibition and facilitation dependent on prime frequency, whereas pseudoword primes behave similarly to low-frequency words. Pseudowords do not possess lexical representations and therefore activate their lexical neighbours in the mental lexicon, but fail to suppress them, thus leading to facilitation (e.g. Andrews & Hersch, 2010; Davis & Lupker, 2006; Forster & Davis, 1991; Forster & Veres, 1998; Segui & Grainger, 1990). Prime lexicality and frequency have been explained in the following way: form priming that is inhibitory indicates lexical competition between items, while form priming that is facilitatory suggests sublexical overlap between the prime and target (Andrews & Hersch, 2010; Davis & Lupker, 2006). This indicates that for word targets preceded by *pseudoword* primes, the processing would primarily be affected by partial sublexical overlap, boosting the recognition of the target.

The dual-route model (Coltheart, Rastle, Perry, Langdon & Ziegler, 2001) consists of two routes: the non-lexical and the lexical route. The former involves decoding letter strings from print to speech using letter-sound rules, whereas the latter encompasses direct access to the mental lexicon to locate the word. The mental lexicon includes knowledge of the word's pronunciation and spelling. This is not an all-or-none route, as both routes are activated during word recognition. The speed at which a particular route is used is affected by target lexicality and NHD. The lexical route is more likely to be used than the non-lexical route for words with a large neighbourhood, as the target shares more orthographic and phonological segments with its neighbours in the mental lexicon. This large overlap strengthens the encoding and retrieval of the items in the mental lexicon (Coltheart et al., 2001), enabling the words to reach their threshold of activation more quickly in the lexical route. In contrast, words with few neighbours reach threshold activation more slowly, have less overlap with items in the mental lexicon and are more weakly encoded. The representations are not strengthened, thus the non-lexical route is more likely to be used than the lexical route. In turn, words with few neighbours would take longer to retrieve and decode than words with many neighbours. For pseudowords, the non-lexical route is more likely to be used than the lexical route, as pseudowords do not possess a lexical representation. The speed of the non-lexical route is affected by NHD. Pseudowords with dense neighbourhoods appear word-like and are more likely to activate lexical representations than pseudowords with sparse neighbourhoods. As a result of activating lexical representation, pseudowords with many neighbours would take longer to reject than a pseudoword with few neighbours.

Third, it has also been demonstrated that phonology contributes to visual word recognition. Orthographic neighbours provide a measure of activation at the orthographic level but are confounded with phonological overlap. Phonology is a key component for reading acquisition, spelling and reading ability (Bradley & Bryant, 1983; Hatcher, Hulme & Ellis, 1994; Share, 1995; Unsworth & Pexman, 2003). Several studies (e.g. Ashby & Rayner, 2004; Carrasco-Ortiz, Midgley, Grainger & Holcomb, 2017; see review by Rastle & Brysbaert, 2006) have demonstrated that the phonological codes of a word are accessed quickly and automatically. Evidence with single word recognition studies, using LDT, has shown that once orthographic NHD is kept constant and phonological NHD is manipulated, words with dense phonological neighbourhoods are recognised faster than words with sparse phonological neighbourhoods (Yates, 2005; Yates, Locker Jr & Simpson, 2004). In addition, Grainger, Muneaux and Ziegler (2005) used a single word LDT and manipulated both phonological and orthographic NHDs. They found no main effects of orthographic or phonological NHDs. When both orthographic and phonological neighbours were matched in terms of NHD - both dense or sparse -, word targets with dense neighbourhoods were responded to more quickly than those with sparse neighbourhoods, while the converse was demonstrated when orthographic and phonological neighbours were not matched in terms of NHD. The authors concluded that target words with a large phonological neighbourhood and a dense orthographic neighbourhood, and vice versa for a sparse neighbourhoods, lead to an increase in compatibility across orthographic and phonological representations. This produces a stronger magnitude of co-activation among candidates. However, target words with large phonological neighbourhoods and a sparse orthographic neighbourhood, and vice versa for a dense orthographic neighbourhood, lead to increased incompatibility across orthographic and phonological representations. This induces a stronger level of interference, indicating that both orthography and phonology are important for the recognition of words (see also Frisson, Bélanger, & Rayner, 2014). In the present study, phonological and orthographic NHD will therefore be controlled.

To summarise, the masked priming effects on the recognition of written words depend on several parameters such as NHD, prime lexicality and frequency for word targets. Furthermore, these factors affect the difficulty of word-nonword discrimination and the magnitude of lexical competition and form priming. In addition, phonological and orthographic NHD affects visual word processing. To resolve mixed findings and provide a clearer insight into competition resolution, the present study used individual differences in spelling and print exposure (orthography), phonological processing (phonology) and reading comprehension and vocabulary (semantics) to disentangle the facets of the Lexical Quality Hypothesis (LQH) to masked priming. The masked priming paradigm has been shown to be sensitive to individual differences that define the early stages of lexical retrieval from those of the decision processes in LD (see review by Andrews, 2012, 2015). This results from the prime being processed unconsciously by the participant, without any decision strategies or anticipatory behaviour affecting the prime.

Effects of the quality of lexical representations

One hypothesis that considers how individual differences modulate skilled lexical retrieval is the LQH (Perfetti, 2007, 2017; Perfetti & Hart, 2001; 2002). Prominent facets of lexical quality are precision (i.e. the speed of, and direct access to, the lexical information pertaining to a representation; Andrews, 2012, 2015), redundancy (i.e. the mapping between orthographic and phonemic strings; Perfetti, 1992) and semantic coherence (i.e. the strength and quality of the underlying lexical representations in terms of orthography, phonology and semantics; Andrews, 2012, 2015). The more precise the lexical representation, the more orthographic and phonological features become bonded so that they are intrinsic to each other. As a result of this redundant mapping, the lexical representation of this specific word is directly activated with its neighbouring candidates being easily suppressed. In turn, this accelerates lexical retrieval. In contrast, less skilled readers have less precise lexical representation and depend more on orthographic representations than phonological. This occurs because the phonological information is not reliably related to the orthography such that the mapping between orthography and phonology does not get consolidated. This leads to a less coherent and more unstable lexical representation in terms of orthography, phonology and semantics. As a corollary, the lexical representation of the particular word takes longer to be activated, as its neighbouring candidates require more time to be supressed.

Perfetti (2007) proposed that vocabulary level and reading comprehension are a measure of semantic coherence. People with good lexical representations can easily suppress competitors as a result of fast and efficient word reading, leaving attentional resources free for higher-level or less practised skills, such as reading comprehension. People with poor lexical representations would struggle to decode the word as a result of competitors, thus resources are dedicated to low-level skills instead of higher-level or less practised skills. Less skilled readers struggle to suppress semantic competitors more than skilled readers (Landi & Perfetti, 2007). Poor comprehenders struggle to draw inferences during online comprehension tasks and answer fewer comprehension questions correctly than good comprehenders (Cain & Oakhill, 1999; Cain, Oakhill & Bryant, 2004; Gernsbacher & Robertson, 1995). This suggests that higher semantic coherence is related to more automatic and modular lexical retrieval mechanisms. However, the construct of orthographic precision is not captured by reading comprehension, thus they may not be related to lexical precision but only semantic coherence, as several cognitive mechanisms contribute to vocabulary and reading comprehension, such as verbal working memory (e.g. Nation, Adams, Bowyer-Crane, & Snowling, 1999).

Developmental and skilled reading studies using masked priming have provided further evidence for orthographic precision in lexical retrieval. Castles, Davis, and Letcher (1999) used 30 frequent word targets with dense neighbourhoods and 30 frequent word targets with sparse neighbourhoods. Each target was preceded by identity primes (e.g. ball-BALL), pseudoword form primes (e.g. dall-BALL) and control primes (e.g. lift-BALL). The authors found that there was no form priming for dense neighbourhoods in adults, while eight-year-old children did show facilitatory priming. Longitudinal evidence is provided by Castles, Davis, Cavalot and Forster (2007), who aimed to measure the recoding process for words with dense neighbourhoods in third graders (eight-year olds) and adult skilled readers. They used 27 frequent word targets with dense neighbourhoods, together with pseudoword form primes (e.g. gorse-HORSE) and replicated Castles et al.'s (1999) findings. After two years, the authors re-tested the third graders when they became fifth graders (10-year olds). This time, they found that fifth graders performed similarly to adults. Forster and Taft (1994) argued that the density constraint effect occurs as a consequence of more similar-looking/sounding candidates entering the mental lexicon. The lexical representation for dense neighbours is thus re-coded from a letter to body-level (i.e. the letters after the vowel, e.g. ive for live, jive, hive, etc.). This leads to lexical representations with dense neighbourhoods to become more precisely tuned and less likely to be activated by form-related primes. For words with sparse neighbourhoods, there are few neighbours to compete, thus the lexical representation for sparse neighbourhoods remains driven by the letter-level. The detectors for words with sparse neighbourhoods would therefore be more broadly tuned to tolerate a fair degree of mismatch. Taken together, these studies support the notion that the development of a precise lexical representation is a gradual process that allows the discrimination between an item and its neighbours in the individual's vocabulary size.

Orthographic precision has been found to be related to spelling ability. Andrews and Hersch (2010) assessed whether spelling ability explained unique variance in masked priming beyond reading comprehension and vocabulary and provided a measure of the orthographic precision component of the lexical quality. They found the density constraint effect shown in

Forster and Davis (1984) and Castles et al. (2007), but this effect was modulated by spelling ability. Poor spellers showed facilitatory priming effects, irrespective of NHD, while good spellers showed facilitatory priming for word targets with sparse neighbourhoods and inhibitory priming for word targets with dense neighbourhoods. This indicates that lexical representations become more finely tuned for words with dense neighbourhoods.

To further assess the role of orthographic precision concerning letter order in competition resolution, Andrews and Lo (2012) compared the effects of nonword neighbour primes (e.g. cire-CURE) with transposed-letter primes (i.e. all the letters of the target word in a different order; e.g. colt-CLOT). To disentangle the unique effects of spelling from those of overall language proficiency, a Principal Component Analysis (PCA, see further) was used to define two orthogonal components: a factor of language proficiency that involved spelling, vocabulary and reading comprehension, and a component that was a subtraction between spelling and reading/vocabulary (i.e. a spelling-meaning factor). Andrews and Lo (2012) observed that the priming effects of transposed and neighbour primes were modulated by language proficiency. High language-proficient readers showed facilitatory priming effects for word targets preceded by nonword neighbour primes and inhibitory priming for those preceded by transposed word primes. In addition, there was a unique effect of the spelling-meaning factor above the language proficiency effects that modulated the priming effect for transposed and neighbour primes. People with a low spelling-meaning factor showed an overall facilitatory priming effect for transposed and neighbour primes, while people with a high spelling-meaning factor demonstrated inhibitory priming in both transposed and neighbour primes, especially for the former. These studies support the LQH, as overall language proficiency is linked to efficient and fast processing of the briefly presented prime. Language proficiency taps into the broader levels of the LQH, while the spelling-meaning factor taps into the early stages (i.e. orthographic precision) of the LQH (see also Andrews & Lo, 2013; Andrews et al., 2017). The spelling-meaning factor reflects the ability to resolve ambiguous information about letter order, with spelling ability seen as an index of orthographic precision. In contrast, the more general properties of high-quality representations, such as tight constituent binding and semantic coherence, modulate lexical competition.

Although these studies have used spelling - an orthographic measure – or reading comprehension and vocabulary – semantic measures, phonology has not received the same level of scrutiny. As stated previously, phonology is important for visual word recognition and despite the importance of phonology for visual word recognition used, there is a surprising lack of phonological measures used in these studies. This makes it difficult to attribute the lexical processes that may be needed to understand the underlying individual differences that define skilled reading. Adelman et al. (2014) argued that orthographic competition is confounded with phonological competition and that phonological NHD explains more variance in masked priming than orthographic NHD. They concluded that the effects seen in masked priming are phonological in nature (cf. Rastle & Brysbaert, 2006). However, the underlying definition of phonology is unclear, as phonology can constitute a wide variety of different behaviours such as phonological working memory, measures of reading fluency, and phonological awareness, inter alia (Melby-Lervag, Lyster & Hulme, 2012). In addition, orthographic precision may be confounded with phonological precision, as lexical retrieval requires multiple constituents (i.e. orthographic, phonological and semantic) to be activated in order to efficiently retrieve the word from the lexicon as a 'unitary word perception event' (Perfetti & Hart, 2001, p.69). Phonological processing needs to be considered to understand how lexical precision and redundancy interact and modulate lexical retrieval, especially for the redundancy principle which focuses on phonological processes. It is therefore important to include measures of phonological ability to assess which component of phonology is essential for lexical precision.

An additional problem with assessing the facets linked to lexical quality is that more skilled readers are better at reading as measured by print exposure, together with sub-processes such as vocabulary, reading comprehension and phonological processing, than less skilled readers (e.g. Acheson, Wells & McDonald, 2008; Burt & Fury, 2000; see review by Huettig, Lachmann, Reis & Petersson, 2018; Martin-Chang & Gould, 2008). This makes it difficult to assess which facet of the LQH, such as semantic coherence, orthographic precision or redundancy, modulates lexical retrieval.

The facet of phonological precision is conflated with orthographic precision and semantic coherence. This makes it hard to assess the the principles of redundancy and lexical precision in isolation. Pseudowords therefore allow us to focus on the redundancy factor. Perfetti (2007, 2017) argued that more skilled readers have more bonded orthographic and phonological features that are characteristic of each other. Skilled readers would try to access the pseudoword target directly. However, as pseudowords have no lexical representation, skilled readers would reject pseudowords more easily. In contrast, for less skilled readers, the orthographic and phonological features are weakly bonded. The graphemes do not have a one-to-one mapping, as the grapheme of <ai> in the pseudoword "haid" activates several phonemic representations: /ai/, /a/, and perhaps /ae/ among many others. This activates multiple representations that result in low activation of the pseudoword. In turn, the pseudoword takes longer to be processed and accessed. Less skilled readers would therefore treat words and pseudowords (more) alike. Andrews and Hersch (2010) supported this hypothesis by showing that people with higher vocabulary knowledge or reading speed were faster at rejecting pseudoword targets. This indicates that the speed of rejecting pseudowords was affected by the redundancy and semantic coherence facets of the LQH. However, no priming effects for pseudoword targets were shown to interact with any individual differences. This suggests that the early stages of lexical processing may not be involved in the decoding of pseudowords, as the early stages of word recognition would occur during the processing of the prime. The prime is processed below conscious awareness and less time and strategic influence would be used to process it, thus semantics would have less influence on processing than orthography and phonology. We further investigate the role of sublexical overlap and lexical competition by including pseudoword targets. Pseudowords preceded by pseudoword primes would enable us to assess the early stages of orthographic and phonological processing. In addition, pseudowords preceded by word primes would allow us to determine the influence of lexical processes on the pseudoword target. We compared word and pseudoword primes for the same pseudoword targets. Our aim was to disentangle the facilitatory effects of sublexical overlap from lexical competition and to assess the redundancy and lexical precision components for the LQH. The present study therefore investigated whether priming effects for pseudoword targets interacted with any component of the LQH.

To summarise, the general prediction of the LQH for word recognition is that orthographic precision should be linked to reduced facilitatory priming in word targets, as high orthographic precision would lead to a fast suppression of the prime and its neighbouring candidates, including the target, especially if the prime is more frequent than the target. People with less precise orthographic or phonological representations should show a larger masked form priming effect, as suppression of the prime and its neighbouring candidates is slower. However, there is conflicting evidence as to what facets of the LQH are involved for a robust lexical representation. By testing word and pseudoword primes and targets, and using a suite of individual difference measures, we can assess which facets of the LQH contributes to competition resolution, providing insight into the mechanisms involved in word recognition and whether varying levels of lexical representation play a role. If phonology provides the best measure of lexical precision, people with high phonological ability should be more likely to demonstrate inhibitory form priming than those with low phonological ability for word targets only. If phonology is purely a measure of redundancy, the same priming effects shown for word targets should be replicated in pseudoword targets.

METHOD

Participants

Ninety-two participants took part in the study. Six participants withdrew after the first two sessions[3]. To ensure that our participants did not have a diagnosis of dyslexia, we excluded two participants from the analyses who performed below 2SD in individual difference measures that assessed phonology, reading fluency and spelling (see section on standardised tests). This left us with a final sample of 84 monolingual British undergraduate students (77 females and 9 left-handed) aged 19-23 years (*M* = 20.18 ±1.04 years), who were given course credits in return for their participation. The experiment was conducted in accordance with British Psychological Society ethical guidelines and was approved by the University of Birmingham's ethical committee (ERN_15-1236). All participants had normal or corrected-to-normal vision and signed a consent form to participate in the study.

To reduce experimenter bias, we analysed the data only after all participants had completed the testing. Based on Andrews and Hersch's (2010) analysis of the interaction among spelling, relatedness and NHD, we estimated Cohen's *d* to be 0.59 and 0.62[4]. Following G*Power 3.1.9.4

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[3] The six participants did not differ in demographic and individual standardised test results (all *F*s < 1) from the main group and their data were excluded from all further analyses.
[4] The equation performed to calculate partial eta was from Richardson (2011):

$$\eta^2 = \frac{(df1 * F)}{(df1 * F + df2)}$$

(Faul, Erdfelder, Buchner & Lang, 2009), power analysis for a paired t-test was computed. However, the paired t-test only assesses specific conditions in the three way-interaction. We therefore adjusted the alpha value (i.e. 0.05) and divided it by the number of conditions used (i.e. 8) to produce an alpha value of 0.00625. Based on this adjusted alpha value, we approximated that a minimum of 59 participants and 56 items in total would produce sufficient power (β = 0.95) in a conventional within-subjects and within-item analysis, to test the interaction of spelling, relatedness and NHD. However, effect sizes are shown to be over-estimated in published studies, especially if they are underpowered and a larger sample size is required to produce adequate power (e.g. Brandt et al., 2014; Button et al., 2013). We therefore tested more participants (*N* = 84) than recommended by traditional power analysis to also be more conservative. In addition, we used general linear mixed models (GLMM), which is more sensitive than a traditional analysis (Baayen, Davidson & Bates, 2008; Barr, Levy, Scheepers & Tily, 2013). Both of these measures mean that we expected our ability to detect the small effects to be enhanced relative to Andrews and Hersch (2010). All scripts, data and materials for the experiment are available at the open science framework at https://osf.io/b2cep/.

From Andrews and Hersch's (2010) study, we inputted the following values in the equation: the numerator degrees of freedom (df1) was 1, The F-values for subjects and items were 7.75 and 7.72 respectively, plus the denominator degrees of freedom (df2) were 93 for within-subject and 77 for within-items.

$$0.08 = \frac{(1 * 7.75)}{(1 * 7.75 + 93)}$$

The partial eta (0.08 for within-subjects and 0.09 for within-items) was then transformed into Cohen's *d*, following the equation of Brysbaert and Stevens (2018):

$$d = \sqrt{\frac{(4 * \eta^2}{1 - \eta^2}}$$

Subsequently, we inputted the partial eta squared value to attain a Cohen's *d* of 0.59 and 0.62 for subjects and items, respectively.

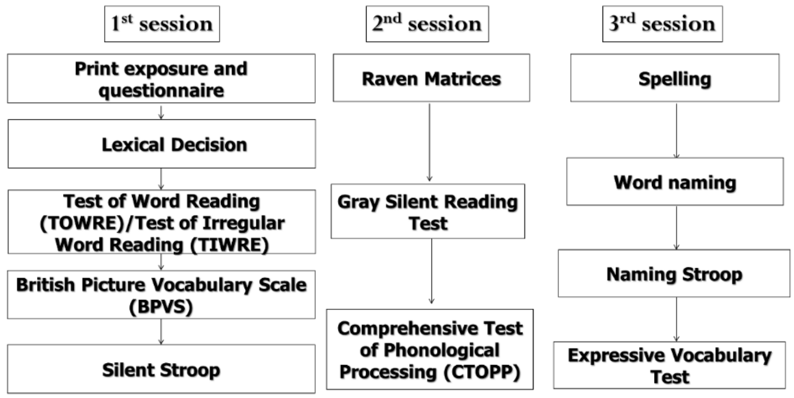

Figure 2.1. An overview of the three experimental sessions

Table 2.1. The individual difference measures used in the current experiment and their groupings.

Tests	Administration	Measures
	Orthography	
Author and title recognition test	Mark known authors and book titles, respectively	Print exposure
Spelling	Spell the word dictated	Spelling
	Phonology	
Phoneme elision	Remove a phoneme from a real word to form a new word	Phonological awareness
Memory for digits	Recall numbers in the same order	Phonological working memory
Nonword repetition	Repeat nonwords	Phonological working memory
Phoneme reversal	Reversal of pseudowords to form an existing word	Phonological processing
Rapid letter naming	Read letters as fast as you can	Grapheme-phoneme conversion
	Reading Fluency	
Test of word reading efficiency: Sight word efficiency	Read words for 45s	Word decoding
Test of word reading efficiency: Phoneme decoding	Read pseudowords for 45s	Phonological decoding
Test of irregular word reading efficiency	Read irregular words	Lexical reading
	Semantics	
Expressive vocabulary test	Answer the question in relation to the picture	Expressive vocabulary
British Picture Vocabulary Scale	Choose out of 4 pictures that reflect the word said	Receptive vocabulary
Gray silent reading test	Read stories and answer questions	Comprehension
Raven's standard progressive matrices	Fit the overall patterns with missing panels	Non-verbal intelligence
	Inhibitory Control	
Naming Stroop	Name the font colour, not the word	Verbal competition resolution
Manual Stroop	Match the font colour and the word	Non-verbal competition resolution

Tests

General procedures for the tests. Each participant completed all components of the study over three sessions. Each session lasted approximately an hour (See Figure 2.1. and Table 2.1. for an overview of the experiment). All participants completed the tests in the same order.

Demographic questionnaire.

This questionnaire collected background information on participants, including age, gender and handedness (See https://osf.io/b2cep/ for questionnaire).

Language measures.

Print exposure. Print exposure included ART and MRT adapted with Stanovich and West (1989) and TRT adapted from Cunningham and Stanovich (1990). The ART is a checklist which requires participants to choose whether they are familiar with the name of a popular author by ticking their name. The ART checklist consists of 100 authors (50 real and 50 foils). The MRT and TRT followed the same procedures as the ART, with participants ticking familiar magazines (MRT) and book titles from plays, poetry and novels (TRT). The TRT checklist had 100 book titles (50 real and 50 foils) and the MRT was a checklist of 100 magazines (50 real and 50 foils)[5]. We modified the lists, which were constructed about 30 years ago for a US audience, to include current and classic authors, together with book titles from Amazon's top 100 authors and book titles and UK magazines from Wikipedia to adapt to a British audience (See https://osf.io/b2cep/ for ART, TRT and MRT). We tested this version of ART, TRT and MRT using a total of 100 additional participants from the same undergraduate population, none of whom participated in the present study. Pilot testing showed a normal distribution among the participants. This confirms that the modifications

[5] We gave all participants the MRT but will not include it in all of the analyses, as nowadays magazines tend to be read infrequently, as reflected in the low recognition score compared to the TRT and ART (Table 2.4.).

of the ART, MRT and TRT were suitable to measure print exposure in the present population. There was no time limit for completing the checklists. For each participant, a score was calculated by subtracting the correct score (i.e. hits) from the number of foils (i.e. false alarms) ticked.

Receptive vocabulary. The BPVS (Dunn, Dunn, Whetton & Burley, 1997) was used to measure the participants' receptive vocabulary. Participants heard a word and selected the corresponding picture from a choice of four. Each participant completed six vocabulary sets (Sets 9-14, with 12 words per set). E-prime (E-studio, E-prime 2.0) software was used to implement this task. The number of correct answers out of 71 was used in the analyses.

Phonological decoding. The sight word efficiency and non-word reading (phonemic decoding) subtests from the TOWRE (Togesen, Wagner & Rashotte, 1999) TIWRE (Reynolds & Kamphaus, 2007) were used as a measure of phonological decoding skill. The tests required participants to read out loud as many printed words out of 108 (TOWRE sight word reading efficiency) or pronounceable pseudowords out of 66 (TOWRE phonemic decoding subtest) as possible within 45 seconds. For the TIWRE, participants had to read 25 irregular words with no time limit. The number of correct answers in each test was recorded for each participant.

Phonological processing. The following subtests from the CTOPP (Wagner, Torgesen & Rashotte, 1999) were used: phoneme elision, rapid letter naming (RLN), memory for digits, non-word repetition and phoneme reversal. In the phoneme elision task, participants had to remove the stated phoneme from a word and report the resulting word (e.g. *mat* without /m/ is *at*). In the non-word repetition task, participants heard pseudowords and had to repeat them back to the experimenter. In the phoneme reversal task, participants heard a pseudoword and had to reverse the pseudoword to form a real word (e.g. *na* forms *an*). In all three tasks there were 18 items and the number of correct answers was recorded. In the RLN, participants had to name 36 printed letters as quickly as possible[6]. In the memory for digits test, participants heard a string of digits which they had to repeat to the experimenter immediately and in verbatim. There were 20 items and the number of correct answers was used in the analyses.

Reading comprehension. In the GSRT (Wiederholt & Blalock, 2000), each participant read six brief stories (i.e. Stories 4-9) silently. The stories increased in complexity. The participant had to answer five multiple choice questions per story with no time limit. E-prime software was used to implement this task. The number of correct answers was used in the analyses.

Expressive vocabulary. In the EVT (Williams, 2007), participants had to name objects (e.g. binoculars) or to describe what a person was doing (e.g. singing) with reference to a picture. There were 109 items and the number of correct answers was used in the analyses.

Spelling. The spelling subtest was based on the British Ability Scale (BAS, Elliott, Smith & McCulloch, 1996). Twenty words were dictated to the participant, which they had to spell accurately. The number of correctly spelled words was used in the analyses.

Executive function measures.

Manual Stroop task. This task required participants to indicate whether a font colour and a word (font: Arial, size: 34) were the same or not. For instance, if participants saw the word BLUE with the font colour blue (congruent), they had to press 'YES' with their dominant hand to indicate they were the same. If the font colour was red instead of blue (incongruent), they had to press the ‘NO’ button with their non-dominant hand to indicate they were different. This test allows us to investigate the role of inhibitory control during word recognition. Each trial began with a fixation cross of 500ms followed by the target, to which they had to respond within 2000ms. The present study used 25 incongruent trials and 75 congruent trials for the Stroop tasks, forcing participants to maintain the goal of word naming rather than focusing primarily on the

[6]The rapid letter naming task is often used as a fluency, as opposed to phonological measure.

goal of colour naming (e.g. Jacoby, Lindsay & Hessels, 2003). Responses were made using a computer keyboard. E-prime (E-studio, E-prime 2.0) software was used to implement this task. Reaction time (in ms) and accuracy were recorded**.** An inverse efficiency score (IES) was calculated (Bruyer & Brysbaert, 2011; Townsend & Ashby, 1978), which is an aggregated measure to combine speed and accuracy in one measure. The equation is below:

$$IES = \frac{RT}{PC}$$

IES is calculated by dividing reaction time (RT) by the proportion of correct responses (PC); smaller numbers indicate greater efficiency (Bruyer & Brysbaert, 2011).

Naming Stroop task. Participants saw a coloured word and had to name the font colour, not the word (font: Arial, size: 34; Stroop, 1935). For instance, participants saw the word BLUE with the font colour blue (congruent) and had to say BLUE. If the font colour was red instead of blue (incongruent), they had to say RED. The same procedure and scoring system were used as for the Manual Stroop task. The responses (i.e. reaction time in ms) were recorded via a voice key and Sony DAT recorder (PCM-M1) for future offline analysis of the naming accuracy data.

Non-verbal intelligence measure. In the Raven's Standard Matrices test (Raven, 1960), participants were shown 60 patterns of increasing complexity and had to select which pieces completed each complex pattern. E-prime (E-studio, E-prime 2.0) software was used to implement this task. The number of correct answers was used in the analyses[7].

Materials for masked priming

Word target set. The experimental targets were a set of 80 monosyllabic words. There were 78 four-letter and two five-letter words. The targets were divided into two equal sets that differed

[7] The Raven's Standard Matrices, Manual Stroop and Naming Stroop were included as control measures for future research to ensure that the differences between groups did not result from non-verbal intelligence or inhibitory control (see Elsherif, Wheeldon & Frisson, under review b, under review c) and were not included in PCA.

in their orthographic and phonological neighbourhood densities (NHD) (see Tables 2.2 and 2.3). The High NHD set had nine or more orthographic neighbours (ON) and 14 or above phonological neighbours (PN), whereas the Low NHD set had between two and eight ON and between three and 13 PN. The low NHD had 3.5 phonographic neighbours (SD = 1.76, range = 1-8), while the high NHD had 03 phonographic neighbours (SD = 2.78, range = 2-12). Both sets significantly differed from each other (ON: $t(78) = 17.72$, $p < .001$, $d = 4.01$; PN: $t(78) = 15.26$, $p < .001$, $d = 3.46$; PgN: $t(78) = 6.64$, $p < .001$, $d = 1.50$). High and low-N targets did not differ significantly in mean word frequency per million ($t < 1$), log frequency ($t(78) = 1.84$, $p = .07$, $d = 0.42$)) or word length (number of graphemes; $t < 1$). The high and low NHD target sets differed in length on average by less than one phoneme, however, this difference was significant ($t(78) = 9.35$, $p < .001$, $d = 2.11$). All frequency and N values were obtained from the CELEX database (Baayen, Piepenbrock & van Rijn, 1993) using Davis's (2005) N-Watch. The full set of material can be found in Table A1 and A2 in the appendix A for a complete list of stimuli.

Pseudoword target set. Eighty monosyllabic pseudoword targets were created to provide the no trials for the lexical decision task. There were 78 four-letter and two five-letter pseudowords. All pseudowords were orthographically legal and pronounceable letter strings in English. The targets were divided into two equal sets differing in orthographic NHD. The high NHD set for pseudowords had eight or above orthographic neighbours, while the low NHD set had between two and seven orthographic neighbours. Both sets were significantly different ($t(78) = 12.31$, $p < .001$, $d = 2.8$). For both sets, there were no significant differences between the word target and pseudoword target for orthographic density (high NHD: $t(78) = 1.22$, $p = .23$, $d = 0.28$; low NHD: $t(78) = 1.67$, $p = .10$, $d = 0.38$). Neighbourhood density could, therefore, not be used as a strategy to indicate whether the target stimulus was a word or pseudoword.

For each word and pseudoword target, related and unrelated word and pseudoword primes were selected (see Tables 2.2 and 2.3). All word and pseudoword primes were monosyllabic and had the same number of letters as their targets.

Word prime set. Related and unrelated word primes had a higher word frequency per million and log word frequency than their target words (all *ps* $< .001$) as primes with higher frequency than the target tend to produce the strongest inhibitory NHD effect (see review by Grainger, 1992) The related word primes differed from their targets by one letter (either the last or penultimate, e.g. peep-PEEK/fate-FAGE). For each NHD set, the primes were selected according to the same NHD criteria as their targets. The primes and targets did not differ significantly from each other in mean orthographic and phonological NHD (word prime-word target: all *t*s < 1; word prime-pseudoword target for high NHD: $t(39) = 1.57$, $p = .12$, $d = 0.50$; word prime-pseudoword target for low NHD: $t(39) = 1.61$, $p = .12$, $d = 0.52$). The high and low NHD prime sets differed significantly from each other in mean orthographic and phonological NHD (word targets: ON: $t(78) = 16.8$, $p < .001$, $d = 3.80$; PN: $t(78) = 15.47$, $p < .001$, $d = 3.50$; pseudoword target: ON: $t(78) = 15.19$, $p < .001$, $d = 3.44$; PN: $t(78) = 13.5$, $p < .001$, $d = 3.05$). However, the high and low NHD prime sets did not differ significantly in word frequency (word and pseudoword target: $t < 1$) and log word frequency (word target: $t(78) = 1.9$, $p = .06$, $d = 0.43$; pseudoword target: $t(78) = 1.79$, $p = .08$, $d = 0.41$). For each NHD set, the number of phonemes between prime and target was not significantly different (dense and sparse NHD: $t < 1$). The high and low NHD prime sets differed in length on average by $1/10^{th}$ of a phoneme, however, this difference was significant ($t(78) = 7.1$, $p < .001$, $d = 1.61$). In order to create the unrelated word primes, the related primes were re-ordered for each NHD set with an additional criterion of no orthographic overlap (i.e. no letter in the same position) between prime and target (e.g., vile-PEEK/plot-FUNK). The means and *p* values were therefore the same as the related word primes.

To reduce target repetition but allow data collection for all targets in all priming conditions, the pseudoword targets and the word targets were divided into two lists. Each target was presented twice in each list. The two stimulus lists had rotated prime-target combinations across the different conditions, thus all targets occurred in all four prime conditions. For example, list one contained vire-PEEK and peep-PEEK, whilst list two included vile-PEEK and peet-PEEK. The two lists were further separated into four experimental blocks per list. This resulted in a total of eight paired blocks. To accomplish the counterbalancing, we divided half of the items for each condition into these eight paired blocks. The order of presentation of paired blocks was rotated across participants. Within each paired block, the two lists had a different order to reduce any systematic effects of the sequencing of items.

Table 2.2. Descriptive statistics for word target characteristics.

	Word Freq	Log Freq	No of Letters	No of Phonemes	Orthographic NHD	Phonological NHD
High NHD						
Target	7.6	0.8	4	3.1	13.5	23.5
Word Primes						
Related (*peep-PEEK*)	32.8	1.4	4	3.2	13.0	23.2
Unrelated (*vile-PEEK*)	32.8	1.4	4	3.2	13.0	23.2
Pseudoword primes						
Related (*peet-PEEK*)			4		12.6	
Unrelated (*vire-PEEK*)			4		12.6	
Low NHD						
Target	5.7	0.6	4.1	3.8	5.3	8.9
Word Primes						
Related (*fund-FUNK*)	29.4	1.2	4.1	3.8	5.3	9.4
Unrelated (*plot-FUNK*)	29.4	1.2	4.1	3.8	5.3	9.4
Pseudoword primes						
Related (furk-FUNK)			4.1		5.1	
Unrelated (ploq-FUNK)			4.1		5.1	

Note. word frequency per million (Freq) and Neighbourhood Density (NHD), both obtained from the CELEX database.

Table 2.3. Descriptive statistics for pseudoword target characteristics.

	Word Freq	Log Freq	No of Letters	No of Phonemes	Orthographic NHD	Phonological NHD
High NHD						
Target			4		12.6	
Word Primes						
Related (*hail-HAID*)	33.7	1.3	4	3.9	13.4	22.8
Unrelated (*luck-*	33.7	1.3	4	3.9	13.4	22.8
Pseudoword						
Related (*hait-HAID*)			4		12.5	
Unrelated (*lusk-*			4		12.5	
Low NHD						
Target			4.1		4.6	
Word Primes						
Related (clue-CLUS)	28.9	1.1	4.1	3.7	5.3	8.8
Unrelated (*drop-CLUS*)	28.9	1.1	4.1	3.7	5.3	8.8
Pseudoword primes						
Related (*clux-CLUS*)			4.1		4.7	
Unrelated (*drot-CLUS*)			4.1		4.7	

Note. word frequency per million (Freq) and Neighbourhood Density (NHD), both obtained from the CELEX database.

Design

The masked priming experiment had a between-item factor: target lexicality (word vs. pseudoword) and 2 (prime lexicality: word versus pseudoword) x 2(NHD: dense versus sparse) x2 (related versus unrelated) nested within-subject design for each between-item factor.

Procedures

Masked priming. Participants were informed that they would be presented with a letter string. The participant had to press the YES key on the button box if the letter string was a word and the NO key if the letter string was a pseudoword. The YES response was always made with the participant’s dominant index finger. The participants were told that they had to complete the lexical decision task as fast as possible without compromising accuracy. E-prime (E-Prime 2.0) software was used to create the experiment and collect the responses. All stimuli were written in Arial font size 34. No mention was made of the primes. No feedback was provided.

A trial of the masked priming task had the following sequence: a forward mask (#####) was presented for 500ms, which was followed by a prime stimulus in lower case for 50ms and finally, the target stimulus in upper case for 1500ms. Participants had to respond within 1500ms. Following the participant's response, there was an inter-trial interval of 1500ms. Participants first completed 10 practice trials with a similar structure to the experimental trials. The experiment started after the practice trials. After every 40 trials, participants had a short break.

RESULTS

Demographic variables, attrition and cognitive and language tests

Our participants were homogenous in their demographics. All 86 participants were first language English speakers and monolingual. All participants, 83 undergraduate and 1 graduate students, had a similar level of education**.** As can be seen in Table 2.4., there is an appropriate level of variability in all the tests.

Table 2.4. Means and standard deviation of all measures for the neurotypical population.

	Control (*n* = 84)	
Measure	*M* (*SD*)	Range
Author Recognition Test (out of 50)	15.2 (7.7)	2-34
Title Recognition Test (out of 50)	18.6 (6.2)	6-34
Magazine Recognition Test (out of 50)	11.26 (4.60)	4-28
British Picture Vocabulary Scale (out of 60)	41.4 (7.3)	23-57
Expressive Vocabulary Test (out of 118)	71.2 (8)	51-89
TOWRE Sight Word Efficiency (out of 108)	87.3 (11.2)	50-108
TOWRE Phoneme Decoding (out of 65)	57.9 (5.6)	35-66
TIWRE (out of 25)	21.2 (1.9)	17-25
CTOPP Phoneme Elision (out of 20)	16.7 (2.4)	9-20
CTOPP Memory for Digits (out of 21)	16.7 (2.1)	12-21
CTOPP Non-Word Repetition (out of 18)	13.7 (1.7)	8-17
CTOPP Rapid Letter Naming (ms)	26.3 (4.8)	15.3-37.6
CTOPP Phoneme Reversal (out of 18)	11.4 (2.6)	2-16
Gray Silent Reading (out of 30)	22.3 (3.3)	14-28
Raven's Standard progressive matrices (out of 60)	45.5 (6.5)	29-58
Spelling (out of 20)	16.5 (2.4)	10-20
Naming Stroop effect (IES)	190 (137)	17.87-1138
Manual Stroop effect (IES)	134 (97)	-61.67-375

Note. Comprehensive Test of phonological processing (CTOPP), Test of Word Reading (TOWRE), Test of Irregular Word Reading Efficiency (TIWRE) and Inverse Efficiency Score (IES).

Correlation

The number of variables was reduced by calculating the composite scores based on *a priori* predictions. This was conducted as there were 15 variables and 84 participants, thus we would require 15 participants for each variable to be placed in a PCA. A composite measure of vocabulary (ZVocab) was formed by averaging the standard scores of the vocabulary scores, as these measures were two strongly correlated variables (r = .51) to provide a more comprehensive measure of vocabulary ability. To form a composite measure of phonological working memory, ZMemory, the two highly correlated measures of phonological working memory (i.e. nonword repetition and memory for digits; r = 0.43) were combined. In addition, we included three highly correlated measures of reading fluency (TOWRE word reading and Rapid Letter Naming; r = .47, TOWRE phonemic decoding and Rapid Letter Naming; r = .56 and TOWRE word reading and phonemic decoding; r = .56) as one averaged measure to offer a detailed assessment of reading fluency, ZReadingFluency. Finally, two strongly related measures of print exposure (ART and TRT; r = .77) were aggregated to create a measure of print exposure, ZPrintexposure. Table 2.5. summarises the correlations between the composite standard scores with the other individual difference measures. The correlations reflect relationships shown in previous studies, including the relationship between print exposure and vocabulary (e.g. Martin-Chang & Gould, 2008) and print exposure and spelling (e.g. Burt & Fury, 2000). Critically, the degree of collinearity among these various individual difference measures is relatively high (rs ≥ .3). A multi-variate approach, such as PCA, is therefore appropriate.

Table 2.5. Correlations between tasks.

	ZVocab	PE	ZMemory	ZRF	PR	TIWRE	Spell	GSRT
PE	0.16							
ZMemory	0.23^{*}	-0.01						
ZRF	0.10	-0.02	0.26^{*}					
PR	0.32^{**}	0.18^{+}	0.31^{**}	0.19^{+}				
TIWRE	0.25^{*}	0.18^{+}	0.22^{*}	0.31^{**}	0.42^{***}			
Spell	0.37^{***}	0.10	0.04	0.24^{*}	0.27^{*}	0.36^{**}		
GSRT	0.38^{***}	0.28^{**}	0.04	-0.08	0.24^{*}	0.22^{*}	0.06	
ZPE	0.35^{***}	0.07	0.13	0.02	0.15	0.24^{*}	0.43^{**}	0.23^{*}

Note. Standard vocabulary composite measure (ZVocab), Phoneme Elision (PE), Standard phonological working memory composite measure (ZMemory), Standard reading fluency composite measure (ZRF), Phoneme Reversal (PR), Gray Silent Reading Test (GSRT), Test of Irregular Word Reading Efficiency (TIWRE), Standard print exposure composite measure (ZPE). $^{+}p < .10$, $^{*}p < .05$, $^{**}p < .01$ and $^{***}p < .001$.

Principal component analysis

The PCA analysis determined the statistical clustering of the individual difference measures (see Appendix B for the PCA with the individual difference measures included as separate, as opposed to combined, measures). This analysis was carried out using the software package GPA rotation (Bernaards & Jennrich, 2005), within the R statistical programming open code software (R Core Team, 2015). The data from Table 2.5. were entered into a PCA. One variable, CTOPP phoneme elision, which correlated less than .3 was dropped from the analysis. The Kaiser-Meyer-Olkin measure of sampling adequacy was .68, above the commonly recommended value of .50 (Field, 2009). The Bartlett's test of sphericity was significant ($\chi 2$ (28) =113.47, $p < .001$). This showed the correlations between the remaining eight variables were appropriate for PCA. A varimax rotation method was applied to determine orthogonalized estimates of factors.

The initial analysis yielded three factors with eigenvalues greater than Kaiser's criterion of 1. A varimax rotation was performed as the factors did not correlate with each other above .32 (Tabachnick, Fiddell & Ullman, 2007). Only variables with loadings of higher than 0.45 were considered. Based on the loadings, these five factors were assigned construct names indicative of their component variables and are listed in order of variance explained in Table 2.6. Components show positive or negative loadings. Positive loadings give inclusionary criteria and describe the underlying construct of the factor. Negative loadings provide exclusionary criteria and show an inverse relationship to the construct of the factor.

The first factor, accounting for the most variance, includes the composite measure of phonological working memory and the composite measures of reading fluency, phoneme reversal and TIWRE (all positive components). These positive loadings indicate a common underlying phonological precision measure. The variables seem to be linked to a measure of **phonological precision**. This factor could be argued to reflect the redundancy facet of the LQH.

The second factor (in order of variance explained) includes the composite measure of print exposure, the composite measure of vocabulary, and spelling. The positive loadings of the recognition test variables along with spelling and vocabulary, suggest that the factor provides a general index of **orthographic precision**.

The third factor includes Gray Silent Reading comprehension and the composite measure of vocabulary (positive loadings), together with the composite score of reading fluency (negative loadings). This means that the higher the vocabulary and the more accurate an individual's reading comprehension, the poorer the reading fluency scores. The more resources that are dedicated to decoding, the fewer resources are expended for higher-level processes such as semantics. The loadings indicate a common semantic process. Together these patterns could be interpreted as an index of **semantic coherence.**

Table 2.6. Factors produced by the PCA.

Factor 1 Phonological precision	Loading value	**Factor 2** Orthographic precision	Loading value	**Factor 3** Semantic Coherence	Loading value
Zmemory	0.73	Spelling	0.87	GSRT	0.84
Phoneme reversal	0.67	ZPE	0.74	ZVocab	0.54
ZReadingFluency	0.63	ZVocab	0.45	ZReading Fluency	-0.46
TIWRE	0.59				
% variance	*0.23*		*0.22*		*0.17*
Cumulative variance	*0.23*		*0.45*		*0.62*

Note. Standard vocabulary composite measure (ZVocab), Standard phonological working memory composite measure (ZMemory), Standard reading fluency composite measure (ZRF), Gray Silent Reading Test (GSRT), Test of Irregular Word Reading Efficiency (TIWRE), Standard print exposure composite measure (ZPE).

General Linear Mixed Effect model (GLMM)

A general mixed linear analysis was conducted on the reaction time data for word and pseudoword targets using the lme4 package (Bates, Maechler & Dai, 2010). The reaction times were log-transformed. GLMM models were run, including neighbourhood density (sum coded with sparse as intercept), relatedness (sum coded with unrelated as intercept) and prime lexicality (sum coded with pseudoword prime as intercept) as a fixed effect with all slopes and intercepts allowed to vary at random by subject and items. With regard to the lexical decision dataset, target lexicality was also placed into the model as a fixed effect. However, word targets and pseudoword targets were analysed separately to see which factors drove the processing and recognition of words and pseudowords. Furthermore, the three factors from the PCA were entered into the model as a fixed effect and analysed as a continuous variable. The plots demonstrate the priming effect calculated by subtracting the related prime condition from the unrelated one (with positive values indicating facilitation and negative values indicating inhibition) and the continuous PCA data were logged as binary variables (high vs. low). The recoding was done by splitting the data from a variable into two sets so that the number of data points per set was as closely matched as possible.

All continuous variables were centred prior to analysis. In all cases, the maximal random structure model included the interactions of all three conditions with both subjects and items (Barr et al., 2013). This was done to reduce type I and II error rates (Barr et al., 2013; Schielzeth & Forstmeier, 2008). A fully random model was used whenever possible. However, fully specified models often fail to converge. In this case, the item random slope was omitted first for both prime lexicality and relatedness. If this model failed to converge, the three-way interaction for the subject random slope was reduced until convergence was reached. If this did not happen, a non-random model was used (Veldre & Andrews, 2014). The minimal model in the fixed effects structure was isolated using the drop1 function, which identifies the most complex fixed effect explaining the least variance. Standardised beta values and 95% confidence intervals are reported as indications of effect size. Larger beta values indicate larger effects, and narrow confidence intervals indicate more precision. Fixed effects were removed until the model with the minimal Bayesian Information Criterion (BIC) was reached (Schwarz, 1978). ΔBIC implies the difference between the full model and reduced model; a positive ΔBIC indicates that the reduced model is better than the null model. We have included Bayes factor (BF) approximations, using the formula (exp(ΔBIC/2); Raftery, 1995); by using the BF, we compared the relative evidence for different models. For instance, a BF value of 5 implies that the reduced model is five times more likely than the full model. In general, the higher the ΔBIC and BF, the more likely the reduced model is in comparison to the full model. Based on these tests, we created a minimal model, which included the combination of factors that provided the best fit of our data. In the reduced model, factors with a t-value of greater than 2 are considered significant at the alpha = .05 level (Baayen et al., 2008).Finally, Cohen's *d* = ΔM/ σ effect sizes for the within-group comparisons were computed with estimated marginal means (for calculation of ΔM) and total variance from covariance model estimates (for standardization of σ; Cohen, 1988; Westfall, Kenny, & Judd, 2014).

Word targets

The reaction times (RTs) were trimmed, excluding all errors, response times below 200ms and responses ±2.5SD or above from participant's mean response time per condition. Five word items (i.e. BARD, BIDE, BOLL, CRAG and NOOK) produced more than 50% errors and so were removed from the lexical decision analyses, leaving 35 target words per condition. This led to 17.8% of the data being removed in total. Only correct trials were included in the RT analyses. Average RTs, SDs, and the proportion of correct responses for each condition, are shown in Table 2.7. Accuracy was high for all conditions with only minute variability between them. The priming effects were small for accuracy. Since the model did not reach convergence, we will not discuss accuracy further. For word targets, the effects were inhibitory in direction for word primes and facilitatory in direction for pseudoword primes. The model for the lexical decision for the word target did not converge until the item slope was removed, leaving only an item intercept; the three-way interaction was reduced to NHD as an individual factor by itself in the random structure (see appendix C for the final model code for word target and pseudoword target).The output of this model is shown in Table 2.8.

Table 2.7. Mean response times and proportion correct for each prime lexicality, relatedness and NHD condition.

	Word Target				Pseudoword target			
	High N		Low N		High N		Low N	
Prime lexicality	Word Prime	Nonword prime	Word Prime	Nonword prime	Word Prime	Nonword prime	Word Prime	Nonword prime
Related								
RT	613(131)	612(133)	626(147)	613(135)	677(150)	679(152)	633(133)	632(139)
P correct	.91(0.28)	.91(0.28)	.88(0.33)	.88(0.32)	.88(0.32)	.88(0.33)	.96(0.19)	.96(0.20)
Unrelated								
RT	608(126)	616(129)	620(132)	625(128)	680(151)	692(157)	630(128)	643(143)
P correct	.91(0.29)	.91(0.28)	.88(0.32)	.88(0.33)	.89(0.32)	.88(0.33)	.95(0.22)	.97(0.18)
Priming								
effect	-5	4	-6	12	3	13	-3	11
RT	.00	.00	.00	.00	-.01	.00	.01	-.01
P correct								

Note. Response times (RT); Proportion (P); Response times are measured in milliseconds and standard deviations are in parentheses.

Table 2.8. The minimal model output for RTs for word target[8].

Fixed Effects	Estimate	Std. Error	95% LCI	95% UCI	*t* values
(Intercept)	6.3950	0.0142	6.3674	6.4228	451.45
Priming conditions					
NHD	0.0131	0.0152	-0.0164	0.0433	0.86
Relatedness	0.0131	0.0056	0.0023	0.0240	2.36*
Prime lexicality	0.0113	0.0045	0.0023	0.0201	2.48*
Individual Factors					
Orthographic precision	-0.0296	0.0093	-0.0438	-0.0065	-3.19*
Phonological precision	-0.0312	0.0096	-0.0415	-0.0053	-3.26*
Interactions					
NHD * relatedness	0.0080	0.0064	-0.0049	0.0203	1.25
Relatedness * prime lexicality	-0.0235	0.0064	-0.0360	-0.0108	-3.65*
Phonological precision * NHD	-0.0166	0.0049	-0.0236	-0.0040	-3.38*
Phonological precision * relatedness	-0.0069	0.0046	-0.0181	0.0002	-1.52
Phonological precision * NHD * relatedness	0.0151	0.0065	0.0037	0.0292	2.34*

Note. * $p < .05$

[8] We also re-analysed our data for word and pseudoword targets with the analytical approach of Andrews and Lo (2012). This was to ensure that any differences across studies did not result with different analytical approaches. When using the same analytical approach, the same pattern of results was found.

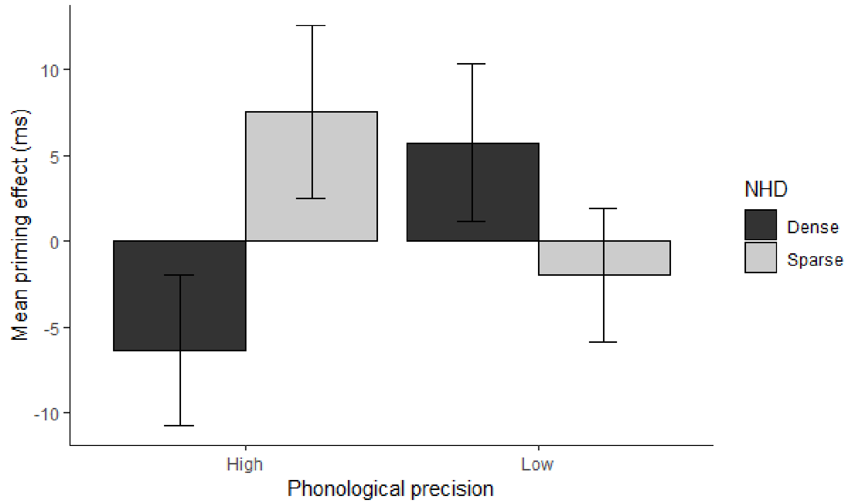

Figure 2.2. Reaction time (RT) priming effects (in ms) for high- and low-N targets, averaged over prime lexicality and separated by the phonological precision composite. Positive priming effects reflect facilitation for targets preceded by related primes, relative to unrelated primes. Error bars represents 95% confidence interval for each condition.

The reduced model was significantly different from the full model (Full model BIC: -6930.8; reduced model = BIC: -7286.3, $p < .001$, ΔBIC: 355.38, Approx. BF > 10,000), thus the final model is based on the reduced model. In the reduced model, there was a significant three-way interaction between phonological precision, NHD and relatedness (see Figure 2.2.). Participants with high phonological precision were more likely to show increased facilitatory priming effects for target words with sparse neighbourhoods, whilst they showed increased inhibitory priming effects for those with dense neighbourhoods. Participants with low phonological precision showed increased facilitatory priming effects for target words with dense neighbourhoods, whilst they showed increased inhibitory priming effects for those with sparse neighbourhoods.

The reduced model was split into two sub-models: high phonological precision and low phonological precision. Phonological precision was removed from the equation and the same procedures for the analyses and random structure from the reduced model were applied to the sub-models. In the high phonological precision sub-model, the NHD and relatedness interaction was significant (b = 0.021, t = 2.60, p = .009). Participants with high phonological precision were more likely to show increased facilitatory priming effects for target words with sparse neighbourhoods, whilst they showed increased inhibitory priming effects for those with dense neighbourhoods. No main effects of NHD (b = -0.002, t = -0.15, p = .88) or relatedness (b = 0.009, t = 1.17, p = .24) were found. For the participants with low phonological precision, no interaction between NHD and relatedness was observed (b = -0.007, t = -0.77, p = .44), relatedness (b = 0.01, t = 1.46, p = .14), and the NHD approached significance (b = 0.03, t = 1.67, p = .10).

The sub-model for high phonological precision was split according to NHD: dense and sparse. NHD was removed from the equation and random structure and the same analyses from the reduced model were applied to the sub-models. For participants with high phonological precision, a simple effect of relatedness was shown for target words with sparse neighbourhoods (b = 0.02, t = 2.64, p = .008, d = 0.08), but not for target words with dense neighbourhoods (b = -0.006, t = -1.03, p = 0.30, d = 0.03). Participants with high phonological precision were more likely to show increased facilitatory priming effects for target words with sparse neighbourhoods.

The reduced model also produced a significant interaction of relatedness with prime lexicality (Table 2.8.). The reduced model was split into two sub-models: word targets preceded by word primes and word targets preceded by pseudoword primes. Prime lexicality was removed from the equation and the same procedures for the analyses from the reduced model were applied to the sub-models. An effect of relatedness was significant for the pseudoword priming condition (b = 0.02, t = 3.89, p < .001, d = 0.08), but not the word priming condition (b = -0.007, t = -1.43, p = .15, d = -0.03). For word primes, a related prime resulted in a longer reaction time (M = 620, SE = 15.2) than an unrelated prime (M = 614, SE = 14.1), whilst for pseudoword primes, related primes led to shorter reaction times (M = 612, SE = 14.6) than unrelated primes (M = 620, SE = 14.0).

With regard to the individual factors, the model output showed that there was a significant effect of orthographic precision and phonological precision on log RT. Unsurprisingly, the higher the components of orthographic precision and phonological precision, the shorter the reaction times.

Pseudoword targets

The reaction times (RTs) were trimmed similar to the word target analyses, resulting in the loss of 9.8% of the data. Average RTs, SDs, proportion correct and 95% confidence interval of reaction times for each condition, are shown in Table 2.7. Accuracy data was not analysed as the model did not reach convergence as the accuracy approached ceiling and there was minute variability in the accuracy data. The direction of priming was inhibitory for pseudoword targets preceded by word primes and facilitatory for pseudoword targets preceded by pseudoword primes. The model for the lexical decision focusing on the pseudoword target did not converge until the item-slope was removed, leaving only an item-intercept, and the three-way interaction for subjects was reduced to individual effects with prime lexicality being removed in the random structure. The minimal model output is shown in Table 2.9. Participants responded slower to pseudowords with dense neighbourhoods than pseudowords with sparse neighbourhoods.

Table 2.9. The minimal model output for RTs for pseudoword targets.

Fixed Effects	Estimate	Std. Error	95% LCI	95% UCI	t values
(Intercept)	6.5080	0.0148	6.4784	6.5367	439.88
Priming conditions					
NHD	-0.0759	0.0153	-0.1058	-0.0459	-4.97*
Relatedness	0.0158	0.0046	0.0068	0.0249	3.42*
Prime lexicality	0.0012	0.0045	-0.0076	0.0099	-0.26
Individual Factors					
Orthographic precision	-0.0281	0.0095	-0.0400	-0.0020	-2.95*
Phonological precision	-0.0306	0.0095	-0.0500	-0.0119	-3.21*
Interactions					
Relatedness * prime lexicality	-0.0146	0.0063	-0.0270	-0.0022	2.31*

Note. * $p < .05$

The reduced model for pseudoword targets was significantly different from the full model (Full model BIC: -6954.1; reduced model = BIC: -7309.0, p <.001, ΔBIC: 354.90, Approx. BF > 10,000). We therefore chose the reduced model for our analyses. The reduced model produced a significant interaction for relatedness and prime lexicality. The reduced model was split into two sub-models: pseudoword targets preceded by a word prime and pseudoword targets preceded by a pseudoword prime. Prime lexicality was removed from the equation and the same procedures for the analyses from the reduced model were applied to the sub-models. The effect of relatedness was not significant for pseudoword targets preceded by a word prime condition (b = 0.0001, t = 0.03, p = 0.98, d < .001), while an effect of relatedness was significant for the pseudoword targets preceded by a pseudoword prime condition (b = 0.016, t = 2.9, p = .005, d = .07). For pseudoword primes, related primes resulted in shorter reaction times (M = 655, SE = 2.68) than unrelated primes (M = 666, SE = 2.76). For word primes, there was no difference in reaction times between related (M = 654, SE = 2.59) and unrelated primes (M = 654, SE = 2.58).

With regard to the individual factors, the model output showed that there was a significant effect of orthographic precision and phonological precision on log RT. As expected, the higher the phonological precision and orthographic precision, the shorter the reaction times.

DISCUSSION

Summary of findings

The current study used a suite of individual difference measures to assess which facets of LQH modulate lexical retrieval. In order to investigate competition resolution during word processing, we manipulated NHD and prime and target lexicality in a masked form priming experiment. We observed that a component of lexical representation interacted with NHD and relatedness, such that participants scoring lower on this component only showed significant facilitatory priming while participants scoring higher showed inhibitory priming for word targets with dense neighbourhoods, but facilitatory priming for words with sparse neighbourhoods. This finding is in line with Andrews and Hersch (2010) and Andrews and Lo (2012), though with one important difference: Andrews and colleagues found that the priming effect was moderated by spelling, while we found that the component of phonological precision, rather than spelling, affected the priming pattern observed. We also noted a significant interaction between prime lexicality and relatedness. The direction of the priming effect was inhibitory for word targets preceded by word neighbour primes and the direction of priming for word targets preceded by pseudoword neighbour primes was facilitatory. This interaction is consistent with the findings of Davis and Lupker (2006), supporting their claim that inhibitory priming for word targets following word primes indicates lexical competition, while facilitatory priming for word targets preceded by pseudoword primes suggests sublexical facilitation.

Pseudoword targets with dense neighbourhoods were rejected more slowly than those with sparse neighbourhoods (also in line with Davis & Lupker, 2006), indicating that it is harder to reject a pseudoword when the pseudoword activates several neighbouring word candidates. Furthermore, pseudoword neighbour primes produced significant facilitatory priming for pseudoword targets, and no significant priming effects were shown for those that followed word primes (in line with Forster & Veres, 1998). Finally, several factors (i.e. phonological precision and orthographic precision) moderated the speed at which pseudowords were rejected. Participants with higher phonological precision and orthographic precision took less time to reject pseudowords compared to people with lower phonological precision and orthographic precision. However, none of the individual difference measures interacted with the priming effect.

For word and pseudoword targets, we did not observe a significant effect of relatedness. Word and pseudoword targets preceded by word primes did not show significant inhibitory priming, while those that followed pseudoword primes demonstrated significant facilitatory priming. It should be noted that findings concerning inhibitory priming have been mixed, with studies in the English language showing facilitatory, inhibitory and null priming effects (e.g. Andrews & Hersch, 2010; Davis & Lupker, 2006; Forster & Veres, 1998). The present study used a prime duration of 50ms, while others have varied the prime duration between 40 and 60ms. Davis and Lupker (2006) and Andrews and Hersch (2010) used a prime duration of 57ms and found that inhibitory priming effects were greater than those of the current study. Previous findings have shown that inhibitory effects increase with prime duration (e.g. Grainger, 1992; De Moor, van den Herten & Verguts, 2007). For example, using an incremental priming paradigm (Jacobs, Grainger & Ferrand, 1995), De Moor et al. (2007) showed that a prime duration of 57ms, as opposed to 43ms, increased the magnitude of inhibitory priming by 40ms. At present, it is unclear whether the 7ms difference in prime duration between our study and that of Andrews and Hersch was responsible for the lack of inhibitory priming shown for word targets preceded by word primes and those that followed pseudoword targets.

The role of LQH in masked priming for word targets

One of the main contributions of the present study is the inclusion of a large number of individual difference measures, given that previous research has tended to focus on either a single measure or a few measures. Previous studies have shown spelling and semantics to moderate the size and direction of the priming effect with regard to the NHD (Andrews and Hersch, 2010; Perfetti, 2007). The present study is the first to include measures of phonological processing and showed that the priming effects depended significantly on the component of phonological precision. People with high phonological precision showed inhibitory priming for word targets with dense neighbourhoods, whereas facilitatory priming was demonstrated for word targets with sparse neighbourhoods. People with low phonological precision showed only facilitatory priming, irrespective of NHD. This was not modulated by any measures related to orthography or semantics. Our findings support Adelman et al. (2014) and Rastle and Brysbaert (2006) who argued that phonological processing moderates priming effects from neighbouring candidates. However, the nature of lexical precision is contentious. Perfetti (1992) and Andrews and colleagues posited that greater lexical precision is a property of a good lexical representation. Greater lexical precision would lead to a quick inhibition of lexical competitors, thus increasing the speed of lexical access, while poor lexical precision would lead to a slow suppression of neighbouring candidates, slowing down lexical access. Andrews and Hersch argued that the quality of lexical representations is best reflected by measures of spelling, as spelling is linked to measures of lexical competition, since the representations have to be robust and stable to allow direct lexical access. However, lexical precision is a graded process that correlates with redundancy. Put simply, representations that are fully specified and precise have redundant mapping between letters and sounds. The more redundant the letter and sound correspondence, the more likely the reader can directly access the mental lexicon and recognise the word. The present study found that the phonological precision component may be a more appropriate measure of lexical precision than components including spelling or lexical-semantic processing, as phonological precision includes both lexical precision and redundancy. In this sense, our results extended the research of Andrews and Hersch (2010), as we found that lexical retrieval is driven by low-level processes (i.e. orthography in Andrews & Hersch, phonology in our study) rather than high-level mechanisms (i.e. print exposure and vocabulary)[9]. This is important as it confirms one of the notions of the LQH that redundancy and lexical precision are mutually dependent and are a graded notion. Put simply, the higher the level of phonological precision, the more strongly bonded the orthographic and phonological features so that they are intrinsic to each other, leading to faster lexical retrieval.

In addition, we assessed whether our main null findings for orthographic precision resulted from lack of power. We found that almost all of our 95% confidence intervals fell outside of Andrews and Hersch's (2010) confidence intervals[10]. This was the case for word targets with dense neighbourhoods in people with high orthographic precision (our confidence intervals [3.59, 3.82] vs. Andrews & Hersch's [-26.16, -4.64], and for word targets with dense neighbourhoods in people with low orthographic precision [-3.36, 2.00 vs. 7.08, 34.50] For the two findings, the CIs overlapped (i.e. word targets with sparse neighbourhoods in people with low orthographic precision [6.02, 12.20 vs. -0.46, 22.23]), and also in those for people with high orthographic precision [-7.31, -0.13, vs -1.88, 23.36]. It should be noted that the 95% CIs in our current study

[9] One difference between our study and Andrews and Hersch is that the latter employed two spelling measures compared to only one spelling measure being used in the current study. The two spelling measures were aggregated, forming a more stable measure of spelling that indexes robust orthographic representation.

[10] We thank Sally Andrews for sharing the averages and standard deviation for good and poor spellers.

are considerably narrower than in Andrews and Hersch's. This indicates that our study does not have less power than their study. One explanation for this difference in variance is that we ensured our participants did not have a diagnosis of dyslexia and used a 2SD cut-off in individual difference measures that assessed phonology, reading fluency and spelling. This was done to ensure that our population was relatively homogeneous. Andrews and Hersch did not use phonological measures and might have included people with dyslexia not diagnosed. This may have led to larger variances in their neurotypical population than the current study.

Alternatively, the smaller variance in our study may have also resulted from both orthographic and phonological NHD being controlled, while Andrews and Hersch manipulated only orthographic NHD. Grainger et al. (2005) argue that a dense orthographic neighbourhood with many phonological neighbours leads to an increase in compatibility across orthographic and phonological representations, inducing a stronger magnitude of co-activation among neighbours. This could lead to stronger activation from the semantic representation, as the processing of these words would directly activate the lexical representation of the word. However, the sparse orthographic neighbourhoods used by Andrews and colleagues have sparse and dense phonological neighbourhoods, leading to an increase in incompatibility across orthographic and phonological representations[11]. This may make it difficult to discriminate neighbours, thus not allowing readers to access the lexical representations of the target directly, which is compatible with Andrews and Hersch's notion that low-level processes (i.e. phonological processes) contributed to competition resolution. Further research is needed to examine how individual

[11] Using N-Watch (Davis, 2005), we assessed the range of orthographic and phonological NHD of Andrews and Hersch's (2010) stimuli and found that word targets with dense and sparse neighbourhoods overlapped in terms of orthographic (high: mean = 12.5, SD = 1.96, range = 6-15; low: mean = 3,6, SD = 2.82, range = 1-7) and phonological NHD (high: mean = 22.73, SD = 5.15, range = 15-33; low: mean = 9.85, SD = 6.84, range = 1-31). In our study, there was no overlap of either orthographic or phonological NHD between dense and sparse words.

differences affect the processing of words with compatible and incompatible mapping between orthographic and phonological representations to assess the influence of phonological precision in word recognition.

The role of LQH in masked priming for pseudoword targets

Regarding the rejection of pseudowords, the literature on the processing of pseudoword targets is limited and the LQH does not make precise predictions for these types of stimuli. However, pseudoword targets provide a viable measure of the redundancy facet concerning the LQH. The LQH states that less skilled readers have weakly bonded orthographic and phonological features, as the phonological and orthographic representations have many-to-one mappings (see the <haid> example in the introduction). Readers may therefore take longer to access the mental lexicon and notice that the pseudoword does not exist. Less skilled readers would treat words and pseudowords more similarly. Skilled readers would try to access the pseudoword target directly, as their grapheme-phoneme correspondence is more bonded. However, as pseudowords have no lexical representation, skilled readers would reject them more easily. Several individual difference measures (i.e. phonological precision and orthographic precision) moderated the speed of rejecting pseudowords in our study. Consistent with the LQH, people with higher phonological and orthographic precision rejected pseudowords more quickly than those with lower phonological precision and orthographic precision. Skilled readers with stronger grapheme-phoneme correspondences can allocate more resources to higher-level mechanisms (cf. LaBerge & Samuel, 1974). In contrast, less skilled readers use additional attentional resources to decode words, negatively influencing the resources available for higher-level mechanisms such as semantic processing, thus taking more time to reject pseudowords.

In addition, no individual component was found to moderate the priming effects for the rejection of pseudowords. This partially supports Andrews and Hersch's (2010) findings, who showed that vocabulary knowledge drove the speed of rejecting pseudowords and that priming effects for pseudowords were not affected by any of the individual difference measures. There are two tenable explanations as to why individual differences do not moderate priming effects in pseudoword targets. It could be argued that 'yes' and 'no' decisions are processed differently, as 'no' decisions require more cognitive resources than 'yes' decisions (e.g. Rayner, Chace, Slattery, & Ashby, 2006). However, Perea, Gomez and Fraga (2010) assessed whether masked nonword priming effects were greater when the task involved a 'yes' response to nonwords than when it entailed a 'no' response. The magnitude of priming effects for nonword targets was similar between yes and no responses. They concluded that the priming effect is a lexical process. A second, perhaps more viable, explanation is that word primes are more likely to produce stronger competitors than pseudoword primes, as the latter have no lexical entries. Pseudoword primes may therefore not activate any word neighbours, thus once the pseudoword target appears, inhibitory priming is not shown. This indicates that the inhibitory priming effects are lexical in nature, as such effects are only shown in the current study for word recognition, not the rejection of pseudowords. It is important to note that phonological precision is a measure of not only redundancy but also lexical precision, as the component of phonological precision was found to be limited to only word, not pseudoword, targets.

Future directions

A first issue concerns the question whether phonological precision changes the role of lexical competition in visual word recognition or whether the mechanisms remain similar but follow a slower time course in people with lower phonological precision. If the latter is true, an increase in prime duration would lead to inhibitory priming for people with low phonological precision (cf. Gernsbacher & Faust, 1991). The extra time would enable the system to identify the prime and inhibit its neighbours prior to the presentation of the target. However, if facilitation remains, this would indicate that people with lower phonological precision may recognise words without depending on lexical competition. For instance, in the LDT, people with low phonological precision might use different response criteria, as they may base their decisions on letter/phoneme overlap between the word and its neighbours in the mental lexicon, as opposed to the identification of a single word that results from greater lexical precision (Perfetti, 2007). In a natural reading environment, good word recognition is required and people who struggle with word recognition, such as those with dyslexia, would rely on other cues such as context to compensate for the absence of lexical competition (Stanovich, 1980).

Conclusion

Overall, the current study partially replicated previous findings from the literature and found that facilitatory priming was demonstrated for words with sparse neighbourhoods, while inhibitory priming was shown for words with dense neighbourhoods. These were modulated by components that included phonological precision. Individuals with high phonological precision showed inhibitory priming for dense neighbourhoods and facilitatory priming for sparse neighbourhoods, while individuals with poor phonological precision demonstrated only facilitatory priming, irrespective of NHD. In addition, we found that the speed of pseudoword rejection was affected by the components of phonological precision and orthographic precision. However, there were no effects of the individual components on the priming effect for pseudoword rejection. This indicates that phonological precision is important for the processing of words and that the inhibitory priming effects in recognition tasks are lexical in nature.

CHAPTER 3.

EFFECTS OF INDIVIDUAL DIFFERENCES IN LEXICAL QUALITY: NEIGHBOURHOOD EFFECTS IN PSEUDOWORD AND WORD NAMING[12]

[12]This chapter is currently under review: Elsherif, Wheeldon, L.R., & Frisson, S. Effects of individual differences in lexical quality: Neighbourhood effects in word and pseudoword naming.

ABSTRACT

Two experiments investigated individual differences in the neighbourhood density effect shown during the production of written words and pseudowords. Word and pseudoword targets with dense and sparse neighbourhoods were used in a masked form priming experiment with 84 university students. In addition, individual difference measures of language and cognitive processes were collected, and a principal component analysis was used to group these data into factors. Overall, we observed facilitatory form priming effects for word and pseudoword targets. However, the facilitatory form priming was larger for pseudoword targets and word targets with sparse neighbourhoods compared to those with dense neighbourhoods. Form priming of word targets was also affected by a factor linking to orthographic precision: For people with low orthographic precision, word targets with dense neighbourhoods preceded by word primes showed stronger facilitatory priming than those that followed pseudoword primes. The opposite pattern was shown for word targets with sparse neighbourhoods. People with high orthographic precision only showed facilitatory priming. Facilitatory form priming for pseudoword targets preceded by pseudoword primes was smaller than for those that followed word primes in people with low orthographic precision. The opposite pattern was found for people with high orthographic precision. These results suggest that people with high orthographic precision rely more on the lexical route than the sublexical route and the opposite is the case for people with low orthographic precision. The implications for theories of masked priming in production and the Lexical Quality Hypothesis applied to reading skill are discussed.

Keywords: Lexical Quality Hypothesis; visual word production; orthography; phonology; semantics

INTRODUCTION

Lexical access in reading is a competitive process between the target word and its neighbours (i.e. a word that differs from another word by one letter or sound; Coltheart, Davelaar, Jonasson, & Besner, 1977). For a word to be correctly recognised, competition between a word and its neighbours must be resolved. Individual differences in aspects of reading ability modulate competition resolution (e.g. Andrews & Hersch, 2010). One model that emphasises individual differences in lexical representation is the Lexical Quality Hypothesis (LQH). According to the LQH, lexical representations differ in terms of their *precision* and *redundancy.* According to Perfetti and colleagues, this variable relates to the level of direct access to a lexical representation and the degree of suppression of neighbouring candidates (Perfetti, 2007), as well as the redundancy of lexical representations (i.e. the regularity of mapping between orthographic and phonological strings; Perfetti, 1992, 2007, 2017; Perfetti & Hart, 2001, 2002). For a precise lexical representation, the links between the orthographic and phonological features are redundant, allowing direct access to the mental lexicon. Supporting evidence for this proposal comes from Andrews and Hersch (2010), who used the masked priming paradigm coupled with a lexical decision task (LDT), wherein a prime is briefly presented below the threshold of conscious awareness. Andrews and Hersch found facilitatory form priming for words with a sparse neighbourhood (i.e. words with only a few neighbouring words) and inhibitory form priming for words with a dense neighbourhood (words with many neighbours). This priming was modulated by spelling. Good spellers, who arguably possess greater lexical precision, showed inhibitory priming for word targets with dense neighbourhoods, but facilitatory priming for word targets with sparse neighbourhoods. In contrast, poor spellers only showed facilitatory priming. They concluded that poor spellers have less redundant lexical representations, which encourage the use of grapheme-phoneme conversion. This in turn increases the time required to process the prime, making suppression of a neighbouring target word less likely to occur during prime processing. The target word is therefore pre-activated by the prime but not suppressed - leading to facilitatory priming. Elsherif, Wheeldon and Frisson (under review) extended this research and included a larger suite of individual differences to examine their contribution to competition resolution in word recognition, using the LDT. They replicated Andrews and Hersch's findings, but found that competition resolution was modulated, not by any factors that included spelling but by a factor relating to phonological precision. This factor was negatively related to form priming effects for word targets with dense neighbourhoods (i.e. participants scoring higher on phonological precision measures showed larger inhibitory priming than those who scored lower on phonological precision), while phonological precision did not affect the priming effect for word targets with sparse neighbourhoods. These results suggest that the component of phonological precision is linked to inhibitory effects of lexical competition for word recognition and provide evidence for the LQH in that people with good phonological precision can inhibit competitors more strongly during word recognition. In other words, during masked priming, the target word is suppressed as it is a neighbouring candidate to the prime, thus slowing access to it when presented for lexical decision. The specific goal in the current study was to examine whether similar effects would be evident during reading aloud (visual word naming).

The studies of Andrews and Hersch (2010) and Elsherif et al. (under review) focus on visual word recognition. Although fewer studies have investigated visual word naming, visual word naming offers further insights into visual word recognition that cannot be assessed using the LDT. For instance, visual word naming does not require a decision to be made, allowing us to assess earlier stages of lexical retrieval than the LDT (Cortese, Yates, Schock & Vilks, 2018; Schilling, Rayner & Chumbley, 1998). In addition, compared to the LDT, there are extra mechanisms in naming such as speech planning and the execution of motor articulators, which do not occur during word recognition (Howell, 2002, 2004; Howell & Au-Yeung, 2002). Notwithstanding these differences between the tasks, both recognition and production use similar routes to process words and pseudowords. The Dual Route Cascaded model of reading (DRC; Coltheart, Rastle, Perry, Langdon & Ziegler, 2001) consists of two routes: the non-lexical and the lexical route. The former entails decoding letter strings from print to speech using letter-sound rules (grapheme-phoneme conversion), while the latter involves direct access to the mental lexicon to locate the word. The mental lexicon contains the lexical representation of the word (i.e. orthography, phonology and semantics). Both routes are thought to be activated during word production and the speed of accessing either route depends on NHD (see review by Andrews, 1997). Words with many neighbours share a large number of orthographic and phonological segments with other words in the mental lexicon. This leads to increased activation of these segments and, in turn, faster production of words with many neighbours than those with few neighbours.

Pseudowords do not possess a lexical representation as they have not been encountered before, thus the sublexical route is more likely to be activated. Although NHD affects the production of pseudowords (e.g. McCann & Besner, 1987), it has been argued that this effect may result from pseudowords with dense neighbourhoods possessing many common spelling-sound correspondences which are similar to those in the mental lexicon. In contrast to pseudowords with dense neighbourhoods, those with sparse neighbourhoods share few spelling-sound correspondences with those in the mental lexicon. As a result of this minimal sub-lexical overlap, these pseudowords will receive less sub-lexical support during recognition, making them harder to produce (see review by Andrews, 1997).

However, evidence for the NHD effect in production is mixed. Findings from non-priming experiments have shown either facilitatory NHD effects (i.e. words with dense neighbourhoods are faster to name than those with sparse neighbourhoods; Adelman & Brown, 2007; McCann &

Besner, 1987; Weekes, 1997, in low-frequency words), inhibitory NHD effects (i.e. words with sparse neighbourhoods are named more quickly than those with dense neighbourhoods; e.g. Arnold, Conture & Ohde, 2005; Sadat, Martin, Costa & Alario, 2014; Vitevitch & Stamer, 2006) or no NHD effect (e.g. Adelman, Sabatos, De Vito, Marquis & Estes, 2014; Bernstein Ratner, Newman & Strekas, 2009; Newman & Bernstein Ratner, 2007; Weekes 1997, in high-frequency words). One plausible explanation could be differences in how NHD was calculated. Traditionally, NHD is computed using either phonological or orthographic neighbours, while Adelman and Brown (2007) have demonstrated that both can be important. However, Adelman and Brown, using the naming latencies from Spieler and Balota (1997) and Balota and Spieler (1998), placed predictors in a multiple regression to assess the contribution of orthographic and *phonographic* NHD on naming latencies. Phonographic neighbours are words that differ from other words by one letter *and* one sound, e.g. *stove* and *stone*. They found that orthographic NHD did affect naming latencies but dense phonographic NHD led to faster naming latencies (cf. Peereman & Content, 1995, who demonstrated similar findings for pseudoword targets). Adelman and Brown concluded that dense phonographic neighbours activate both orthographic and phonological neighbours and produce a stronger magnitude of co-activation among orthographic and phonological candidates. The present study will therefore control orthographic, phonological and phonographic NHD for visual word naming.

The relationship between NHD and form priming during reading aloud has received much less attention than that of word recognition and shows different patterns to visual LDT. To our knowledge, only one study has assessed the relationship between NHD and form priming in reading aloud. Forster and Davis (1991) tested participants in a masked form priming paradigm and asked them to name words. Participants were given word targets with dense and sparse neighbourhoods always preceded by a pseudoword prime in the experimental condition (e.g.

gord-GOLD) and always preceded by a word prime in the control condition (e.g. *soil-GOLD*). The authors found that facilitatory form priming was stronger for word targets with dense than sparse neighbourhoods, which is the reverse from what is found in visual LD. They concluded that the stronger priming effect for word targets with dense neighbourhoods results from them possessing more shared phonological segments than that of the sparse neighbourhoods.

There is further evidence to suggests that latencies in reading aloud are sensitive to earlier processes in word processing than LD latencies. Schilling et al. (1998) used a multi-methodological approach that consisted of LDT, naming and eye-tracking. They showed that the total reading times from eye-tracking (i.e. a late measure of reading) were strongly related to the LDT, while visual word and pseudoword naming were strongly related to first fixation duration (i.e. an early measure of reading). In addition, Katz et al. (2012) aimed to determine the role of word reading in 99 poor readers on two standard tasks: LD and visual word naming. The authors observed that although regular words were named more quickly than irregular words (i.e. the regularity effect) in visual word naming, there was no regularity effect in the LDT. In addition, Katz et al. showed that visual word naming is more strongly related to decoding skills (i.e. grapheme-phoneme conversion; Gough & Tunmer, 1986; Katz et al., 2012), as assessed with the Test of Word Reading Efficiency (TOWRE). These findings suggest that reading aloud assesses the early stages of reading and is linked to decoding.

In contrast to LD, visual word naming is more affected by sublexical than lexical processing. Phonological priming is not always observed during visual word recognition but is consistently demonstrated in visual word naming studies (see review by Rastle & Brysbaert, 2006). Form priming in visual word naming is always facilitatory, as opposed to visual word recognition, wherein inhibitory, facilitatory or no priming have been observed (Rastle & Brysbaert, 2006). Word frequency accounts for 40% of the variance in the response latencies in visual LD, while initial phoneme onset describes 2% of the variance of LD performance (Brysbaert & Cortese, 2010; Cortese & Khanna, 2007; Ferrand et al., 2011). In contrast, initial phoneme onset accounts for 40% of the variance for word naming, while word frequency explains less than 10% of the variance (Cortese & Khanna, 2007; Ferrand et al., 2011). Taken together, these studies indicate that lexical and semantic predictors might play more of a role in the LDT than in visual word naming latencies, while sublexical characteristics (i.e. phonological and articulatory) might impact word naming latencies more than LD response times.

Detailed orthographic representations must be formed for accurate and fluent reading in word production. According to the self-teaching theory (Share, 1995), phonological recoding (i.e. learning and mapping graphemes to phonemes; Ziegler & Goswami, 2005) must be fluent before detailed orthographic representations are formed, which can then be used in word recognition. This requires increased reading experience, which improves word reading abilities. It could be argued that different strategies are used by readers with different levels of reading experience. Following the DRC model (Coltheart et al., 2001), more skilled readers would use the lexical route, as their phonological recoding is fluent and their orthographic representations are stable. This would allow the reader to depend on high-level measures such as print exposure and vocabulary to decode novel words. In contrast, less skilled readers are more likely to depend on the non-lexical route than the lexical route, as their phonological recoding is less fluent, due to limited and reduced print exposure. Martens and De Jong (2008) assessed the influence of repeated word reading on direct or indirect word reading with regard to word length. The length effect was seen as an index of sublexical letter-sound conversion. They argued that the disappearance of the length effect after repeated word reading would indicate a shift from a non-lexical to a lexical route. The authors found that after 16 repeated word readings, the length effect disappeared, in average and good readers, but persisted for the poor readers in the fourth and fifth grades. The authors concluded that poor readers depend on the indirect route of reading for longer than average and good readers. In addition, Adelman et al. (2014) asked 100 17-to-55 year old participants to read 592 monosyllabic words aloud. They found that word targets with dense neighbourhoods were named more quickly than those with sparse neighbourhoods. In addition, naming latencies were shorter for high-frequency words than low-frequency words. These effects became smaller as the participant's age increased. They concluded that older participants have higher reading experience and vocabulary size, and therefore possess high-quality lexical representations (it should be noted though that vocabulary size and print exposure were not independently assessed). Taken together, these studies support the notion that the development of a precise lexical representation is a result of the shift from the non-lexical to the lexical route. This shift depends on reading experience and vocabulary which makes phonological decoding fluent and results in more stable orthographic representations.

Within the framework of the LQH (Perfetti, 2007), visual word naming has not been assessed or discussed in detail. According to the LQH, articulation is a higher-level mechanism that is a by-product of the lexical representation. In order to examine the role of redundancy in LQH, visual word naming may be a more effective measure than LDT. Visual word naming is primarily driven by sublexical and articulatory properties, as opposed to the LDT, which conflates sublexical and lexical processes (e.g. Cortese & Khanna, 2007; Ferrand et al., 2011). Visual word naming for words and pseudowords may therefore enable the assessment of orthographic precision and redundancy in isolation. According to Perfetti (2007), with more reading experience, grapheme-phoneme conversion becomes more automatic, allowing more resources to be expended for other skills such as articulation. Put simply, more skilled readers possess stronger one-to-one mappings between the graphemes and their phonemic counterparts and can access the mental lexicon directly, since their grapheme-phoneme conversion is automatic. For pseudowords, skilled readers would similarly rely on automatic grapheme-phoneme conversion without access to the mental lexicon. However, less skilled readers possess less developed one-to-one mappings. Less skilled readers would read the grapheme of <ou> in the pseudoword <mouts>, as /oː/, /aʊ/, and perhaps /əʊ/ among other phonemic representations, while more skilled readers would be more likely to say /aʊ/. Because multiple phonemic representations are activated in less skilled readers, competition at the phonological level is increased during production, leading to smaller priming effects. Less skilled readers should show smaller priming effects for word targets with dense neighbourhoods than word targets with sparse neighbourhoods, as there is more competition between phonemes.

Present study

The present study used a word and pseudoword naming task to measure the early stages of word recognition. In addition, we investigated the role of lexical and sublexical processes by including both word and pseudoword primes and targets. Pseudoword targets that followed pseudoword primes enable us to measure the early stages of orthography and phonology (i.e. the redundancy component of the LQH), whereas pseudowords preceded by word primes permit us to assess the outcomes of the lexical processes on pseudoword targets (i.e. the lexical precision component of the LQH). Hence, this design can help disentangle the role of sublexical overlap from lexical competition in the early stages of word recognition and separate the roles of redundancy and lexical precision in visual word naming.

To summarise, this study was designed to investigate whether form priming effects in reading aloud are affected by individual differences and how these relate to the LQH. The general prediction of the LQH is that less skilled readers with less precise/less redundant lexical representations will struggle to suppress the neighbours of the word primes during visual word naming. Consequently, upon seeing the prime, less skilled readers will be less likely to have fully suppressed the word target, which in turn will lead to greater facilitation when presented with the target. In contrast, more skilled readers should show reduced facilitatory priming in word targets: upon seeing the prime, they will quickly suppress neighbouring candidates, including the target. Hence, when the target appears, it will take longer to recognize the word, leading to reduced form priming. The current study used the same standardised tests and participants as Elsherif et al.'s (under review) study, which involved a suite of tests assessing orthographic, phonological, reading fluency and semantic measures. Elsherif et al. (under review) found that phonological precision is a measure of lexical precision. If this is the case, we expect people with high phonological precision to show less facilitatory priming for word targets only than those with low phonological precision. However, based on previous research, if orthographic precision provides the best measure of lexical precision, people with high orthographic precision should demonstrate reduced facilitatory form priming than those with low orthographic precision, at least for word targets. However, if orthographic precision is a measure of redundancy and lexical precision, the priming effects shown for word targets should be replicated in pseudoword targets.

METHOD

Participants

Ninety-two monolingual British undergraduate students with normal or corrected-to-normal vision participated in the current study. All participants had also taken part in Elsherif et al. (under review) and signed a consent form. Six participants withdrew from the study and the data from a further two participants were removed because they performed below 2SD in individual difference measures that assessed phonology, reading fluency and spelling, a level of performance which may be indicative of dyslexia[13]. The remaining 84 undergraduate students (77 females and 9 left-handers) aged 19-23 years (M = 20.18 ±1.04 years) from the University of

[13] The six participants did not differ in demographic and individual standardised test results (all Fs < 1) from the main group and their data were excluded from all further analyses.

Birmingham, participated in the study for course credits. All participants were British English speakers, monolingual and had similar level of education. The experiment was approved by the University of Birmingham ethical's committee (ERN_15-1236) and was aligned with the ethical guidelines of the British Psychological Society.

To reduce experimenter bias, we analysed the data after all participants had completed the testing. Based on Forster and Davis' (1991) analysis of the main effect of relatedness, we estimated Cohen's *d* to be 1.34[14]. Following G*Power 3.1.9.4 (Faul, Erdfelder, Buchner & Lang, 2009), power analysis for paired *t*-test, it was approximated that 10 participants produced sufficient power (β = 0.95) in a conventional min F' analysis to test the main effect of relatedness. Given that we were also interested in testing the interaction between relatedness, NHD and prime lexicality, together with the PCA components, the minimum number of participants required was 60 (as 10 participants were required for each effect and the three identical PCA components, see Elsherif et al., under review). When replicating a past finding, it is recommended that a larger

[14] The equation performed to calculate partial eta was from Richardson (2011):

$$\eta^2 = \frac{(df1 * F)}{(df1 * F + df2)}$$

From Forster and Davis' (1991) study, we inputted the following values in the equation: the numerator degrees of freedom (df1) was 1, The *F* value was 24.66, plus the denominator degrees of freedom (df2) were 55.

$$0.31 = \frac{(1 * 24.66)}{(1 * 24.66 + 55)}$$

The partial eta was then transformed into Cohen's *d*, following the equation of Brysbaert and Stevens (2018):

$$d = \sqrt{\frac{(4 * \eta^2}{1 - \eta^2}}$$

Subsequently, we inputted the η^2 value, producing a Cohen's *d* of 1.34 for subject and items.

$$1.34 = \sqrt{\frac{(4 * 0.31}{1 - 0.31}}$$

sample size is used to ensure adequate power, as effect sizes can be overestimated in published studies, particularly if they are underpowered (e.g. Brandt et al., 2014; Button et al., 2013). Hence, in order to be more conservative, we tested more participants (*N* = 84) than recommended by the traditional power analysis. The alpha set for the study was .05. In addition, we used general linear mixed modelling (GLMM), which is more sensitive than a traditional analysis (Baayen, Davidson & Bates, 2008; Barr, Levy, Scheepers & Tily, 2013). The increase in sample size and GLMM being used meant that we expected our ability to detect the effects to be enhanced relative to Forster and Davis (1991). All scripts, data and materials for the experiment are available at the open science framework at https://osf.io/efq5b/.

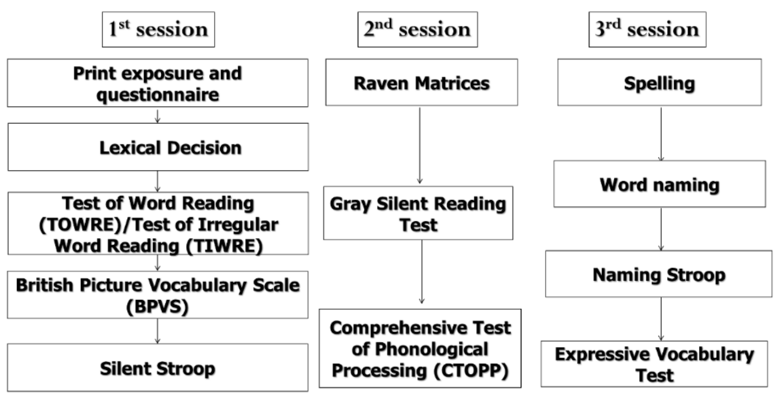

Figure 3.1. An overview of the three experimental sessions

Table 3.1. The individual difference measures used in the current experiment and their groupings.

Tests	Administration	Measures
	Orthography	
Author, title and magazine recognition test[a]	Mark known authors, book titles and magazine, respectively	Print exposure
Spelling[b]	Spell the word dictated	Spelling
	Phonology	
Phoneme elision[c]	Remove a phoneme from a real word to form a new word	Phonological awareness
Memory for digits[c]	Recall numbers in the same order	Phonological working memory
Nonword repetition[c]	Repeat nonwords	Phonological working memory
Phoneme reversal[c]	Reversal of pseudowords to form an existing word	Phonological processing
Rapid letter naming[c]	Read letters as fast as you can	Grapheme-phoneme conversion
	Reading Fluency	
TOWRE: Sight word efficiency[d]	Read words for 45s	Word decoding
TOWRE: Phoneme decoding[d]	Read pseudowords for 45s	Phonological decoding
Test of irregular word reading efficiency[e]	Read irregular words	Lexical reading
	Semantics	
Expressive vocabulary test[f]	Answer the question in relation to the picture	Expressive vocabulary
British Picture Vocabulary Scale[g]	Choose out of 4 pictures that reflect the word said	Receptive vocabulary
Gray silent reading test[h]	Read stories and answer questions	Comprehension
Raven's standard progressive matrices[i]	Fit the overall patterns with missing panels	Non-verbal intelligence
	Inhibitory Control	
Naming Stroop[j]	Name the font colour, not the word	Verbal competition resolution
Manual Stroop[j]	Match the font colour and the word	Non-verbal competition resolution

Note. Test of Word Reading (TOWRE) and Test of Irregular Word Reading Efficiency (TIWRE). [a]Cunningham and Stanovich (1990) and Stanovich and West (1989); [b]Elliott, Smith and McCulloch (1996), [c]Wagner, Torgesen and Rashotte (1999), [d]Togesen, Wagner and Rashotte (1999), [e]Reynolds and Kamphaus (2007), [f]Williams (2007), [g]Dunn, Dunn, Whetton and Burley (1997), [h]Wiederholt & Blalock (2000), [i]Raven (1960) and [j]Stroop (1935).

Tests

General procedures for the tests. Each participant completed all components of the study over three sessions. Each session lasted approximately an hour (See Figure 3.1. for an overview of the study). All participants completed the tests in the same order. Participants were assessed on several measures of orthography, phonology, reading fluency, semantics, non-verbal intelligence and inhibitory control[15], which are described in detail in Elsherif et al. (under review; see Table 3.1.). To provide a broad assessment of lexical quality, the tests selected included three measures of orthographic processing: spelling production, author recognition test and title recognition test[16]; three tests of semantic processing: expressive vocabulary, receptive vocabulary and a passage comprehension test; four reading fluency tests: test of regular word reading, irregular word reading, pseudoword reading and rapid letter naming; and finally, four tests of phonological processing: phoneme elision, phoneme reversal, nonword repetition and memory for digits. They were also given a demographic questionnaire that included questions of age, gender and handedness.

Materials for masked priming

Word target set. The CELEX database (Baayen, Piepenbrock & van Rijn, 1993) using Davis's (2005) N-Watch was used for item selection to obtain all frequency and neighbourhood values for 80 monosyllabic word targets[17]. The 40 words with a sparse neighbourhood had on average 5.3 orthographic neighbours (SD = 1.90; range = 2-8), 9.3 phonological neighbours (SD = 2.92; range = 8-15) and 3.5 phonographic neighbours (SD = 1.76, range = 1-8), whereas the 40 words with dense neighbourhoods had on average 13.0 orthographic neighbours (SD = 2.05, range = 10-18), 23.2 phonological neighbours (SD = 5.90, range = 14-36) and 7.03 phonographic neighbours (SD = 2.78, range = 2-12). Both sets differed significantly from each other (ON: $t(78) = 17.72$, $p < .001$, $d = 4.01$; PN: $t(78) = 15.26$, $p < .001$, $d = 3.46$; PgN: $t(78) = 6.64$, $p < .001$, $d = 1.50$). The word targets were matched between groups (dense vs. sparse) in terms of word length (number of letters) and

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[15] The Raven Matrices, Manual Stroop and Naming Stroop were included as control measures for future research to ensure that the differences between groups did not result from non-verbal intelligence or inhibitory control (see Elsherif, Wheeldon & Frisson, under review b) and were not included in PCA.
[16] We gave all participants the MRT but will not include it in all of the analyses, as nowadays magazines tend to be read infrequently, as reflected in the low recognition score compared to the TRT and ART (Table 2.4.).
[17] The stimuli are the same as those used in Elsherif et al. (under review) and can be found in Appendix A1 and A2.

word frequency. Statistical tests showed that the groups did not differ significantly in these measures (word frequency $t < 1$; log frequency: ($t(78) = 1.84$, $p = .07$, $d = .42$) word length: $t < 1$). While the difference in number of phonemes was less than 1 (3.1 for target words with dense NBH and 3.8 for sparse), this difference was significant ($t(78) = 9.35$, $p < .001$, $d = 2.11$). See Table 3.2. for descriptive. Word naming will be tested in Experiment 1. See Appendix A1 for word targets.

Pseudoword target set. For the purpose of pseudoword naming (Experiment 2), 80 nonwords were created that matched the word targets in word length ($t < 1$) and orthographic NHD (dense NHD: $t(78) = 1.22$, $p = .23$, $d = 0.28$; sparse NHD: $t(78) = 1.67$, $p = .10$, $d = 0.38$). The targets were divided into two equivalent sets differing in orthographic NHD. Pseudowords with dense neighbourhoods had eight or above orthographic neighbours, whereas pseudowords with sparse neighbourhoods had between two and seven orthographic neighbours ($t(78) = 12.31$, $p < .001$, $d = 2.8$). See Table 3.3. for descriptive. All pseudowords conformed to the English spelling rules and were pronounceable using the grapheme-phoneme conversion rules. See Appendix A2 for pseudoword targets.

Prime set. For each word and pseudoword target, related (i.e. prime and target overlap in all letters except one) and unrelated (i.e. no letter overlap between prime and target) word and pseudoword primes were chosen (see Tables 3.2. and 3.3.). All primes were monosyllabic and shared the same number of letters as their targets.

Target words had a lower word frequency than their related and unrelated word primes (all ps < .001). However, the prime and target did not differ in measures of orthographic, phonological and phonographic NHD (all ts < 1) and word length ($t < 1$). The word prime sets for the dense and sparse NHD did not significantly differ in terms of word frequency (word and pseudoword target: $t < 1$). Within each NHD set, the number of phonemes did not differ significantly between prime and target (dense and sparse NHD: $t < 1$). However, even though the number of phonemes for the dense and sparse NHD prime sets only differed on average by less than 1/10th of a phoneme, this difference was significant ($t(78) = 7.1$, $p < .001$, $d = 1.61$). The related primes were re-ordered for each NHD set with an additional criterion of no orthographic overlap (i.e. no letter in the same position) between prime and target (e.g. vire-PEEK/ ploq-FUNK) to create the unrelated word primes. The related and unrelated prime conditions did not differ from each other in terms of word frequency, word length, number of phonemes, orthographic, phonological and phonographic NHD (all *t*s < 1).

Design of the masked priming experiment.

Two counterbalanced lists were created so that data were collected for all targets in all priming conditions for an individual participant. For example, one list would contain vire-peek, and peep-peek and another list vile-peek and peet-peek. Four experimental blocks were made from these two lists to create a total of eight paired blocks to achieve counterbalancing. The order of presentation for the paired blocks was rotated across participants. To reduce any systematic effects of item sequencing, the two lists had a different order in each paired block. The masked priming experiment design involved an orthogonal manipulation of a 2 (prime lexicality: word versus pseudoword) x 2 (NHD: dense versus sparse) x2 (related versus unrelated) nested within-subject design for each between-item factor[5]. There were two differences between the LDT and naming task: The LDT was completed months earlier before the naming task to remove long-term priming effects. In addition, if one list was presented in the LDT (e.g. the list that contained ploq-FUNK and fund-FUNK), the second list was presented for the naming task (e.g. the list that had plot-FUNK and funt-FUNK) to the same participant.

Table 3.2. Descriptive statistics for word target characteristics.

	Word Freq	No of Letters	No of Phonemes	Orthographic NHD	Phonological NHD	Phonographic NHD
Dense NHD						
Target	7.6	4	3.1	13.5	23.5	7.03
Word Primes						
Related (*peep-PEEK*)	32.8	4	3.2	13.0	23.2	7.35
Unrelated (*vile-PEEK*)	32.8	4	3.2	13.0	23.2	7.35
Pseudoword primes						
Related (*peet-PEEK*)		4		12.6		
Unrelated (*vire-PEEK*)		4		12.6		
Sparse NHD						
Target	5.7	4.1	3.8	5.3	8.9	3.53
Word Primes						
Related (*fund-FUNK*)	29.4	4.1	3.8	5.3	9.4	3.50
Unrelated (*plot-FUNK*)	29.4	4.1	3.8	5.3	9.4	3.50
Pseudoword primes						
Related (furk-FUNK)		4.1		5.1		
Unrelated (ploq-FUNK)		4.1		5.1		

Note. word frequency per million (Freq) and Neighbourhood Density (NHD), both obtained from the CELEX database.

Table 3.3. Descriptive statistics for pseudoword target characteristics.

	Word Freq	No of Letters	No of Phonemes	Orthographic NHD	Phonological NHD	Phonographic NHD
Dense NHD						
Target		4		12.6		
Word Primes						
Related (*hail-HAID*)	33.7	4	3.9	13.4	22.8	6.3
Unrelated (*luck-HAID*)	33.7	4	3.9	13.4	22.8	6.3
Pseudoword primes						
Related (*hait-HAID*)		4		12.5		
Unrelated (*lusk-HAID*)		4		12.5		
Sparse NHD						
Target		4.1		4.6		
Word Primes						
Related (clue-CLUS)	28.9	4.1	3.7	5.3	8.8	3.2
Unrelated (*drop-CLUS*)	28.9	4.1	3.7	5.3	8.8	3.2
Pseudoword primes						
Related (*clux-CLUS*)		4.1		4.7		
Unrelated (*drot-CLUS*)		4.1		4.7		

Note. word frequency per million (Freq) and Neighbourhood Density (NHD), both obtained from the CELEX database.

Procedures

Masked priming. Participants were informed that they would be presented with a letter string. Participants were instructed to read the string of letters aloud as fast as possible without compromising accuracy into a microphone connected to a Sony DAT recorder (PCM-M1) for future offline analysis of the naming data. E-prime (E-Prime 2.0) software was used to create the experiment and collect the responses. All stimuli were written in Arial font size 34. No mention was made of the primes. No feedback was provided.

A trial of the masked priming task had the following sequence: a forward mask (#####) was presented for 500ms, which was followed by a prime stimulus in lower case for 50ms and finally, the target stimulus in upper case for 1500ms. Participants had to respond within 1500ms. Following the participant's response, there was an inter-trial interval of 1500ms. Participants first completed 10 practice trials with a similar structure to the experimental trials. The experiment started after the practice trials. After every 80 trials, participants had a short break.

RESULTS

Demographic variables, attrition and cognitive and language tests

Results from the individual difference measures can be found in Table 3.4.

Table 3.4. Means and standard deviation of all measures.

	Control (*n* = 84)	
Measure	*M* (*SD*)	Range
Author Recognition Test (out of 50)	15.2 (7.7)	2-34
Title Recognition Test (out of 50)	18.6 (6.2)	6-34
Magazine Recognition Test (out of 50)	11.26 (4.60)	4-28
British Picture Vocabulary Scale (out of 60)	41.4 (7.3)	23-57
Expressive Vocabulary Test (out of 118)	71.2 (8)	51-89
TOWRE Sight Word Efficiency (out of 108)	87.3 (11.2)	50-108
TOWRE Phoneme Decoding (out of 65)	57.9 (5.6)	35-66
TIWRE (out of 25)	21.2 (1.9)	17-25
CTOPP Phoneme Elision (out of 20)	16.7 (2.4)	9-20
CTOPP Memory for Digits (out of 21)	16.7 (2.1)	12-21
CTOPP Non-Word Repetition (out of 18)	13.7 (1.7)	8-17
CTOPP Rapid Letter Naming (ms)	26.3 (4.8)	15.3-37.6
CTOPP Phoneme Reversal (out of 18)	11.4 (2.6)	2-16
Gray Silent Reading (out of 30)	22.3 (3.3)	14-28
Raven's Standard progressive matrices (out of 60)	45.5 (6.5)	29-58
Spelling (out of 20)	16.5 (2.4)	10-20
Naming Stroop effect (IES)	190 (137)	17.87-1138
Manual Stroop effect (IES)	134 (97)	-61.67-375

Note. CTOPP = Comprehensive Test of Phonological Processing, TOWRE = Test of Word Reading Efficiency, TIWRE = Test of Irregular Word Reading Efficiency, and IES = Inverse Efficiency Score.

Correlation

The number of variables was reduced by calculating the composite scores based on a priori predictions. This was conducted as there were 15 variables and 84 participants, thus we would require 15 participants for each variable to be placed in a principal component analysis (PCA). A composite measure of vocabulary (ZVocab) was formed by averaging the standard scores of the vocabulary measures (i.e. BPVS and EVT), as these measures were strongly correlated (*r* = .51) to provide a more comprehensive measure of vocabulary ability. To form a composite measure of phonological working memory, ZMemory, the two highly correlated measures of phonological working memory (i.e. nonword repetition and memory for digits; *r* = 0.43) were combined. In addition, we included three highly correlated measures of reading fluency (TOWRE word reading and Rapid Letter Naming; *r* = .47, TOWRE phonemic decoding and Rapid Letter Naming ; *r* = .56 and TOWRE word reading and phonemic decoding; *r* = .56) as one averaged measure to offer a detailed assessment of reading fluency, ZReadingFluency. Finally, two strongly related measures of print exposure (ART and TRT; *r* = .77) were aggregated to create a measure of print exposure, ZPrintexposure. Table 3.5. summarises the correlations between the composite standard scores with the other individual difference measures. The correlations reflect relationships shown in previous studies, including the relationship between print exposure and reading comprehension (e.g. Acheson, Wells & MacDonald, 2008). Importantly, the collinearity between these individual difference measures is relatively high (*r*s ≥ .3), thus it is appropriate to use a multi-variate approach such as PCA.

Table 3.5. Correlations between tasks.

	ZVocab	PE	ZMemory	ZRF	PR	TIWRE	Spell	GSRT
PE	0.16							
ZMemory	0.23^{*}	-0.01						
ZRF	0.10	-0.02	0.26^{*}					
PR	0.32^{**}	0.18^{+}	0.31^{**}	0.19^{+}				
TIWRE	0.25^{*}	0.18^{+}	0.22^{*}	0.31^{**}	0.42^{***}			
Spell	0.37^{***}	0.10	0.04	0.24^{*}	0.27^{*}	0.36^{**}		
GSRT	0.38^{***}	0.28^{**}	0.04	-0.08	0.24^{*}	0.22^{*}	0.06	
ZPE	0.35^{***}	0.07	0.13	0.02	0.15	0.24^{*}	0.43^{**}	0.23^{*}

Note. Standard vocabulary composite measure (ZVocab), Phoneme Elision (PE), Standard phonological working memory composite measure (ZMemory), Standard reading fluency composite measure (ZRF), Phoneme reversal (PR), Gray Silent Reading Test (GSRT), Test of Irregular Word Reading Efficiency (TIWRE), Standard print exposure composite measure (ZPE). $^{+}p < .10$, $^{*}p < .05$, $^{**}p < .01$ and $^{***}p < .001$.

Principal component analysis

The PCA analysis determined the statistical clustering of the individual difference measures (see Appendix B for the PCA with the individual difference measures included as separate, as opposed to combined, measures). The software package, GPA rotation (Bernaards & Jennrich, 2005), was used to carry out this analysis in the R statistical programming open code software (R Core Team, 2015). The data from Table 3.5. were entered into a PCA. One variable was dropped from the analysis as it correlated less than .3 with any other variable (i.e. CTOPP phoneme elision). The Kaiser-Meyer-Olkin measure of sampling adequacy was .68, above the commonly recommended value of .50 (Field, 2009). The Bartlett's test of sphericity was significant ($\chi2$ (28) =113.47, $p < .001$), indicating that the remaining seven variables were suitable for the PCA. A varimax rotation method was applied since the factors did not correlate with each other above .32 (Tabachnick, Fiddell & Ullman, 2007) and to determine orthogonalized estimates of factors.

The three components of the current study are identical to Elsherif et al. (under review). The analysis showed three factors with eigenvalues greater than Kaiser's criterion of 1. Variables were considered if they had a loading factor above .45. We assigned names to these three components that were suggestive of their component variables. The components are listed in the order of variance described in Table 3.6. The loadings in these three factors were either positive or negative. Positive loadings give inclusionary criteria and describe the underlying construct of the factor. Negative loadings provide exclusionary criteria and show an inverse relationship to the construct of the factor.

The first factor, describing most of the variance, includes the composite measure of phonological working memory and the composite measures of reading fluency, phoneme reversal and TIWRE (all positive loadings). The positive loadings of these measures suggest that this factor reflects a measure of **phonological precision**. This factor could be posited to reflect the redundancy facet of the LQH.

The second factor includes the composite measure of print exposure, composite measure of vocabulary and spelling (all positive loadings). The positive loadings of the recognition test variables, together with spelling and the composite measure of vocabulary, indicate these patterns could be interpreted as a general measure of **orthographic precision**.

The third factor involves Gray Silent Reading Comprehension and the composite measure of vocabulary (positive loadings), along with the composite score of reading fluency (negative loadings). The worse the reading fluency scores, the higher the vocabulary and an individual's reading comprehension. The fewer the resources are dedicated to decoding, the more resources are applied to the higher-level processes such as semantics. These loadings suggest a common semantic process. Together, these patterns could be interpreted as an index of the **semantic coherence** facet of the LQH.

Table 3.6. Factors produced by the PCA.

Factor 1 Phonological precision	Loading value	**Factor 2** Orthographic precision	Loading value	**Factor 3** Semantic Coherence	Loading value
Zmemory	0.73	Spelling	0.87	GSRT	0.84
Phoneme reversal	0.67	ZPrint exposure	0.74	ZVocab	0.54
ZReadingFluency	0.63	ZVocab	0.45	ZReading Fluency	-0.46
TIWRE	0.59				
% variance	*0.23*		*0.22*		*0.17*
Cumulative variance	*0.23*		*0.45*		*0.62*

Note. Standard vocabulary composite measure (ZVocab), Phoneme Elision (PE), Standard phonological working memory composite measure (ZMemory), Standard reading fluency composite measure (ZRF), Phoneme Reversal (PR), Gray Silent Reading Test (GSRT), Test of Irregular Word Reading Efficiency (TIWRE), Standard print exposure composite measure (ZPE).

General Linear Mixed Effect model (GLMM)

Statistical analyses were conducted using linear mixed effects models with the statistical package R (R Core Team, 2015) with the lme4 package (Bates, Maechler & Dai, 2010). These analyses were conducted on the naming latencies for word and pseudoword targets. The naming latencies were log-transformed to correct the positive skew related to raw naming latencies. The GLMM models included three fixed effects: NHD (sum coded with sparse neighbourhood), relatedness (sum coded with unrelated as intercept) and prime lexicality (sum coded with pseudoword prime as intercept). In addition, the three components from the PCA were included into the model as fixed effects and analysed as a continuous variable. The factors were centred. Subjects and items were treated as crossed random effects. Random intercepts were included for both subjects and items. Relatedness, prime lexicality and NHD were involved as an interaction for random by-subject slopes, whereas prime lexicality and NHD were included as random-by-item slopes (i.e. maximal random structure model; Barr et al., 2013; Schielzeth & Forstmeier, 2008). A maximal random structure model rarely converges. If convergence does not ensue, the interaction was first simplified for the random-by-item slope followed by the random-by-subject slope until convergence was reached. If convergence does not occur, a non-random model was implemented (Veldre & Andrews, 2014). Standardised beta values and 95% confidence intervals are shown as measures of effect sizes. Narrow confidence intervals reflect more precision, while larger beta values suggest larger effects.

We started with a full model, and performed a step-wise reduction procedure (using the drop1 function in R) to remove fixed effects and to locate the minimal model using Bayesian Information Criterion (BIC) to find the lowest BIC, indicating better goodness of fit (Schwarz, 1978). The difference between the full model and reduced model formed ΔBIC; a positive ΔBIC indicates that the reduced model is better than the null model. In addition, Using the formula (exp(ΔBIC/2); Raftery, 1995), we calculated approximate Bayes factor (BF) to compare the relative evidence between the full model and reduced models. For instance, a BF value of 10 suggests that the reduced model is 10 times more likely than the full model to occur. These measures were used to create a minimal model and provide the best fit for our data. In general, the higher both ΔBIC and BF, the more likely the reduced model is likely to explain the data in comparison to the full model. We had used an absolute *t* value greater than 2.00 to suggest that the variable was significant at the $\alpha = .05$ level (Baayen et al., 2008). Effect sizes were calculated using Cohen's $d = \Delta M / \sigma$ for the within-group comparisons. These were computed with estimated marginal means (for calculation of ΔM) and total variance from the covariance model estimates (for standardization of σ; Cohen, 1988; see review by Westfall, Kenny, & Judd, 2014 for calculation). For any interaction that included the effect of relatedness, the plots show the priming effects computed as related primes were subtracted from unrelated primes (i.e. negative priming effects suggests inhibitory priming, whereas positive priming effects indicates facilitatory priming) and the factors from the PCA were transformed from continuous to categorical variables (high vs.

low). The recoding was completed, using a median split, so the number of data points were matched evenly.

Word targets

The naming latencies data for each participant in each condition was subjected to a ± 2.5 standard deviation trim. Any naming latencies below 200ms was also removed. Only RTs for correct responses were used in the analyses. One word item, 'BASS', produced more than 50% of errors and was removed from the analyses, leaving 39 target words per condition. In total, 6.18% of the data was removed prior to analyses. Average RTs, SDs and the proportion of correct responses for each condition, are shown in Table 3.7. Accuracy was high for all conditions with only minute variability between them. The priming effects were small for accuracy. For word targets, the effect was facilitatory for word primes and inhibitory for pseudoword primes. Since the model did not reach convergence, we will not discuss accuracy further. For reaction times, the priming effects were facilitatory for word targets, with the priming effects being smaller for words with dense neighbourhoods than those with sparse neighbourhoods.

Table 3.7. Mean response times and proportion correct for each prime lexicality, relatedness and NHD condition for word naming.

	High N		Low N	
Prime lexicality	Word prime	Pseudoword prime	Word prime	Pseudoword prime
Related				
RT	594 (121)	603 (124)	595 (138)	593 (125)
P correct	.96 (0.19)	.95 (0.21)	.97 (0.18)	.96 (0.19)
Unrelated				
RT	612 (117)	614 (119)	619 (128)	619 (131)
P correct	.95 (0.21)	.96 (0.19)	.98 (0.19)	.97 (0.17)
Priming effect				
RT	18	11	24	26
P correct	.01	-.01	.01	-.01

Note. Response times (RT); Proportion (P); Response times are measured in milliseconds and standard deviations are in parentheses.

The model for the word naming task did not converge until the item-slope was removed, leaving only a random item-intercept, and the three-way interaction was reduced to NHD and relatedness as individual factors by themselves in the random structure of the subject (see appendix C for the final model code). The minimal model with the same random structure is shown in Table 3.8.

Table 3.8. The minimal model output for RTs in the word naming task.

Fixed Effects	Estimate	Std. Error	95% UCI	95% LCI	t values
(Intercept)	6.3790	0.0152	6.4067	6.351	420.37
Priming conditions					
NHD	-0.0160	0.0099	0.0035	-0.0357	-1.6
Relatedness	0.0208	0.0063	0.0327	0.0087	3.3*
Prime lexicality	-0.0136	0.0061	-0.0017	-0.0257	-2.3*
Individual Factors					
Orthographic precision	0.0039	0.0143	0.0325	-0.0192	-0.3
Phonological precision	-0.0259	0.0121	-0.0084	-0.0534	-2.1*
Interactions					
NHD * prime lexicality	0.0107	0.0085	0.0276	-0.0058	1.3
NHD * relatedness	0.0198	0.0085	0.0365	0.0031	2.3*
Prime lexicality *relatedness	0.0119	0.0086	0.0289	-0.0049	1.4
Orthographic precision * NHD	0.0063	0.0066	0.0166	-0.0092	1.0
Orthographic precision * prime lexicality	0.0012	0.0062	0.0132	-0.0112	0.2
Orthographic precision * relatedness	0.0036	0.0064	0.0127	-0.0113	0.6
NHD * prime lexicality * relatedness	-0.0069	0.0120	0.0165	-0.0305	-0.6
Orthographic precision * NHD * prime lexicality	-0.0149	0.0086	0.0032	-0.0306	-1.7
Orthographic precision * NHD * relatedness	-0.0125	0.0086	0.0107	-0.0231	-1.5
Orthographic precision * prime lexicality * relatedness	-0.0114	0.0088	0.0051	-0.0291	-1.3
Orthographic precision * NHD * prime lexicality * relatedness	0.0400	0.0123	0.0616	0.0138	3.2*

Note. * $p < .05$

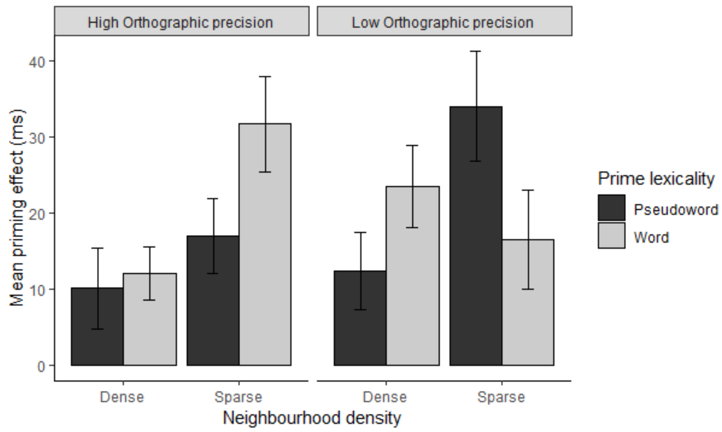

Figure 3.2. Reaction time (RT) priming effects (in ms) for high- and low-N targets preceded by word and pseudoword primes and separated by the orthographic precision composite. Positive priming effects reflect facilitation for targets preceded by related primes, relative to unrelated primes. Error bars represent 95% confidence interval for each condition.

Although the reduced model was not significantly different from the full model (Full model: AIC: -8503.4, BIC: -7945.2; reduced model = AIC; -8540.4, BIC: -8354.4, p = .10, ΔBIC: 409.12, Approx. BF > 10,000), the reduced model produced an approximate Bayes factor above 10,000 and a higher ΔBIC values than the full model, suggesting that the removal of these variables improved the model fit and that the reduced model is more likely to occur at least more than 10000 times than the full model. The final model is therefore based on the reduced model. In the reduced model, there was a four-way interaction between orthographic precision, neighbourhood density, prime lexicality and relatedness (Figure 3.2.). There was a decreased facilitatory priming for target words with dense neighbourhoods with increasing orthographic precision. For target words with sparse neighbourhoods preceded by pseudoword primes, there was a decreased facilitatory priming effect with increasing orthographic precision. The reverse is shown for target words with sparse neighbourhoods preceded by word primes. The full model was split into two sub-models: high orthographic precision and low orthographic precision models. Orthographic precision was removed from the equation and the same procedures for the analyses and random structure from the full model were applied to the sub-models. In the high orthographic precision model, there was interaction of NHD, prime lexicality and relatedness that approached significance (b = 0.003, t = 1.8, p = .08). Participants with high orthographic precision showed a reduced facilitatory priming for word targets preceded by pseudoword primes compared to word primes following word targets with sparse neighbourhoods. The same results were demonstrated in word targets with dense neighbourhoods.

The confidence intervals shown in Figure 3.2 supports that there is a difference in word targets with sparse neighbourhoods in people with high orthographic precision, despite the fact that the interaction approached significance. We therefore split the high orthographic precision model was split into two sub-models: dense neighbourhoods and sparse neighbourhoods, as a clear difference is observed. NHD was removed from the equation and the same procedures for the analyses and random structure from the full model were applied to the sub-models. For word targets with dense neighbourhoods, there was no interaction of prime lexicality and relatedness (b = 0.004, t = 0.35, p = .73), there was a significant simple effect of relatedness (b = 0.02, t = 2.82, p < .001) and a significant simple effect of prime lexicality (b = -0.02, t = -1.87, p = .02). Participants with high orthographic precision showed facilitatory priming in word targets with dense neighbourhoods. In addition, people with high orthographic precision responded faster to word targets with dense neighbourhoods that were preceded by word primes than those that followed pseudoword primes. For target words with sparse neighbourhoods, there was a significant interaction of prime lexicality and relatedness (b = 0.03, t = 2.69, p = .007) such that word targets with sparse neighbourhoods that followed word primes showed larger facilitatory priming than those preceded by pseudoword primes.

The sub-model for sparse neighbourhoods for people with high orthographic precision was further split according to prime lexicality: word prime and pseudoword prime. Prime lexicality was removed from the equation and random structure, and the same analyses from the full model were applied to the sub-models. A simple effect of relatedness was significantly observed for word targets that followed word primes (b = 0.06, t = 6.22, p < .001, d = 0.28) and pseudoword primes (b = 0.03, t = 3.52, p < .001, d = 0.15) in people with high orthographic precision who produced word targets with sparse neighbourhoods. People with high orthographic precision were more likely to demonstrate increased facilitatory priming effects for target words with sparse neighbourhoods preceded by pseudoword primes and word primes.

For the sub-model of people with low orthographic precision, an interaction between NHD, prime lexicality and relatedness was found (b = -0.037, t = 2.00, p = .045). Participants with low orthographic precision showed a reduced facilitatory priming for word targets preceded by pseudoword primes compared to word primes following word targets with dense neighbourhoods. However, the converse was shown for word targets with sparse neighbourhoods. The low orthographic precision model was split into two sub-models: dense neighbourhoods and sparse neighbourhoods. NHD was removed from the equation and the same procedures for the analyses and random structure from the full model were applied to the sub-models. For targets with dense neighbourhoods, there was no significant interaction of prime lexicality and relatedness (b = 0.02, t = 1.52, p = .13) and no effect of prime lexicality (b = -0.01, t = -1.32, p = .19). There was a simple effect of relatedness (b = 0.02, t = 2.11, p = .04). For target words with sparse neighbourhood, there was no significant interaction of prime lexicality and relatedness (b = -0.02, t = -1.25, p = .21) and no effect of prime lexicality (b = 0.007, t = 0.83, p = .41). There was a simple effect of relatedness (b = 0.05, t = 5.30, p < .001). Hence, participants with low orthographic precision showed facilitatory priming for word targets with dense and sparse neighbourhoods.

With regard to the individual factors, the model output showed that there was a significant effect of phonological precision on log RT. Unsurprisingly, the higher the components of phonological precision, the lower the reaction times.

DISCUSSION

In Experiment 1, we tested whether the magnitude of the form priming effect would interact with NHD and whether this interaction was modulated by individual differences. Contra to Forster and Davis's (1991) findings, we showed that word targets from a sparse neighbourhood had a larger faciliatory form priming effect than those from a dense neighbourhood. In addition, we found that the component of orthographic precision moderated form priming. People with high orthographic precision only showed facilitatory form priming, irrespective of prime lexicality or NHD. For participants with low orthographic precision, target words with sparse neighbourhoods preceded by pseudoword primes showed a reduced facilitatory form priming effect compared to those that followed word primes. The converse was demonstrated for word targets with dense neighbourhoods. The implications for these findings in relation to LQH will be discussed in the General Discussion. Although the observed form priming effects may result from differing levels of orthographic precision, it is necessary to investigate whether the findings would generalise to pseudoword stimuli and assess whether the observed effects are independent of the lexical status of the items or limited to only a specific lexical category.

Experiment 2: Pseudoword naming

The reaction times (RTs) were trimmed in the same way as for Experiment 1, leading to 6.38% of the data being removed in total. Average RTs, SDs, and the proportion correct responses for each condition, are shown in Table 3.9. Accuracy was again high for all conditions. The priming effects were small for the accuracy measure, with facilitatory effects for pseudoword primes and inhibitory or null effects for word primes. Since the model did not reach convergence, we will not discuss accuracy further. For reaction times, the priming effects for the pseudoword targets were all facilitatory. The priming effects were smaller for pseudowords with dense neighbourhoods than those with sparse neighbourhoods.

Table 3.9. Mean response times and proportion correct for each prime lexicality, relatedness and NHD condition for pseudoword naming.

	High N		Low N	
Prime lexicality	Word Prime	Pseudoword prime	Word Prime	Pseudoword prime
Related				
RT	510 (116)	512 (117)	513 (124)	509 (125)
P correct	.95 (0.22)	.95 (0.22)	.95 (0.23)	.96 (0.21)
Unrelated				
RT	517 (109)	524 (116)	531 (120)	525 (120)
P correct	.96 (0.20)	.94 (0.24)	.95 (0.22)	.95 (0.21)
Priming effect				
RT	7	12	18	16
P correct	-.01	.01	0	.01

Note. Response times (RT); Proportion (P); Response times are measured in milliseconds and standard deviations are in parentheses.

The model for the pseudoword naming task did not converge until the item-slope was removed, leaving only a random item-intercept, and the three-way interaction was reduced to NHD and relatedness as individual factors by themselves in the random structure of the subject (see Appendix C for the final model code). The minimal model with the same random structure is shown in Table 3.10.

Table 3.10. The minimal model output for RTs for pseudoword targets.

Fixed Effects	Estimate	Std. Error	95% UCI	95% LCI	t values
(Intercept)	6.2160	0.0159	6.2420	6.1820	391.32
Priming conditions					
NHD	-0.0121	0.0100	0.0143	-0.0229	-1.2
Relatedness	0.0202	0.0057	0.0311	0.0091	3.6*
Prime lexicality	0.0059	0.0055	0.0106	-0.007	-1.1
Individual Factors					
Orthographic precision	-0.0316	0.0146	0.0092	-0.0464	-2.2*
Phonological precision	-0.0563	0.0144	-0.0010	-0.0516	-3.9*
Interactions					
Prime lexicality * relatedness	-0.0011	0.0064	0.0116	-0.0134	-0.2
NHD * relatedness	0.0168	0.0064	0.0293	0.0043	2.6*
Phonological precision * relatedness	0.0069	0.0035	0.0149	0.0015	2.0*
Orthographic precision * prime lexicality	-0.0084	0.0046	0.0004	-0.0176	-1.8.
Orthographic precision * relatedness	-0.0084	0.0048	-0.0014	-0.0198	-1.8.
Orthographic precision * relatedness * prime lexicality	-0.0170	0.0066	-0.0050	-0.0300	2.6*

Note. *p < .10, * p* < .05

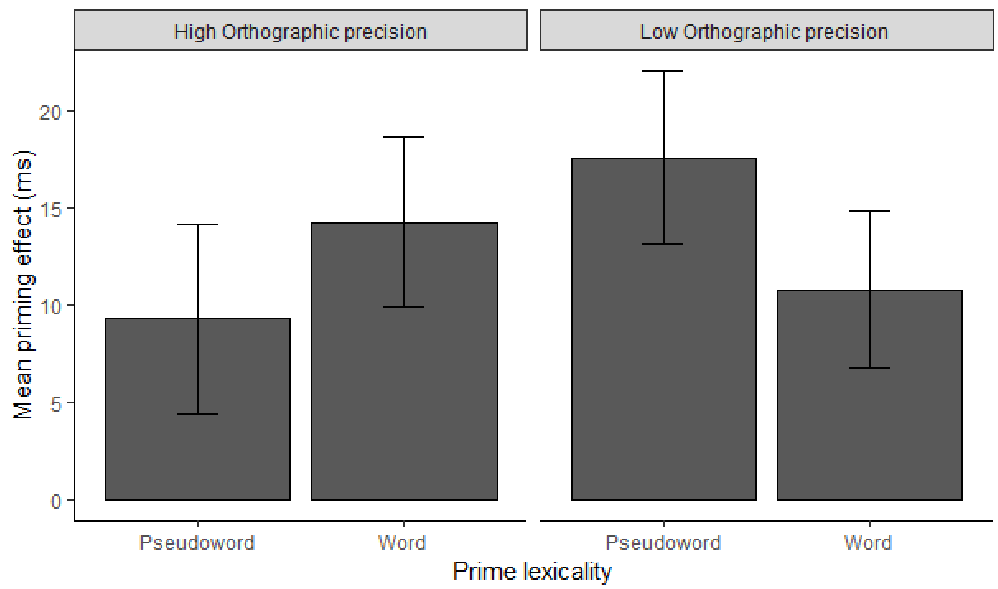

Figure 3.3. Reaction time (RT) priming effects (in ms) for pseudword targets preceded by word and pseudoword primes and separated by the orthographic precision composite. Positive priming effects reflect facilitation for targets preceded by related primes, relative to unrelated primes. Error bars represent 95% confidence interval for each condition.

Although the reduced model was not significantly different from the full model (Full model AIC: -7019.8, BIC: -6871.0; reduced model = AIC; -6971.2, BIC: -6413.2, p = .26, ΔBIC: 457.75, Approx. BF > 10,000), the reduced model produced an approximate Bayes factor above 10,000 and a higher ΔBIC values than the full model, suggesting that the removal of these variables improved the model fit and that the reduced model is more likely to occur at least more than 10000 times than the full model. In the reduced model (see Table 3.10.), there was a significant three-way interaction between orthographic precision, relatedness and prime lexicality (see Figure 3.3.). There was a decreasing facilitatory priming for target pseudowords preceded by pseudoword primes with increasing orthographic precision. The converse was found for target pseudowords preceded by word primes. The full model was split into two sub-models: high orthographic precision and low orthographic precision models. Orthographic precision was removed from the equation and the same procedures for the analyses and random structure from the full model were applied to the sub-models. In the high orthographic precision model, there was no interaction of prime lexicality and relatedness (b = 0.011, t = 1.4, p = .17), and no main effect of prime lexicality (b = -0.002, t = -0.04, p = .72). There was a main effect of relatedness (b = 0.018, t = 2.4, p = .02). Participants with high orthographic precision showed facilitatory priming overall. For the participants with low orthographic precision, no interaction was observed between prime lexicality and relatedness (b =-0.012, t =- 1.08, p = .28), and the effect of prime lexicality was also not significant (b = 0.0049, t = -1.19, p = .23). However, there was an effect of relatedness (b = 0.022 t = 2.51, p = .01). Participants with low orthographic precision showed facilitatory priming for pseudoword targets.

The full model also produced a significant interaction of phonological precision with relatedness (Table 3.10.). Participants with high phonological precision produced a larger facilitatory priming than those with low phonological precision. The full model was split into two sub-models: high phonological precision and low phonological precision. Phonological precision was removed from the equation and the same procedures for the analyses from the full model were applied to the sub-models. An effect of relatedness was shown for both the high phonological precision model (b = 0.02, t = 2.5, p = .013, d = 0.17) and the low phonological precision model (b = 0.02, t = 2.52, p = .012, d = 0.09). For participants with high phonological precision, the presence of a related prime resulted in faster reaction times (M = 479, SE = 1.85) compared to the unrelated prime conditions (M = 494, SE = 1.75). For participants with low phonological precision, unrelated primes resulted in longer naming latency (M = 555, SE = 2.24) than related primes (M = 544, SE = 2.28).

The full model also produced a significant interaction of NHD with relatedness (Table 3.10.). Pseudowords with dense neighbourhoods showed smaller facilitatory priming than those with sparse neighbourhoods. The full model was split into two sub-models: pseudoword targets with dense neighbourhoods and pseudoword targets with sparse neighbourhoods. NHD was removed from the equation and the same procedures for the analyses from the full model were applied to the sub-models. An effect of relatedness was shown for pseudowords with dense neighbourhoods (b = 0.024, t = 3.58, p < .001, d = 0.09) and pseudowords with sparse neighbourhoods (b = 0.033, t = 5.12, p < .001, d = 0.15). For pseudoword targets with dense neighbourhoods, the presence of a related prime resulted in shorter reaction times (M = 511, SE = 2.08) than an unrelated prime (M = 520, SE = 2.01). For pseudoword targets with sparse neighbourhoods, unrelated primes (M = 528, SE = 2.14) led to longer naming latencies than related primes (M = 511, SE = 2.22).

With regard to the individual factors, there was a significant effect of phonological precision and orthographic precision on log RT. Unsurprisingly, the higher the components of phonological precision and orthographic precision, the lower the reaction times.

DISCUSSION

Experiment 2 assessed whether the findings shown in Experiment 1 would replicate for pseudoword targets. Firstly, we found that pseudoword targets with sparse neighbourhoods showed larger facilitatory form priming than those with dense neighbourhoods, similar to the pattern observed in Experiment 1. In addition, we observed that participants with higher phonological precision demonstrated a larger facilitatory form priming effect than those with low phonological precision. We also found a three-way interaction of prime lexicality, relatedness and orthographic precision. People with low orthographic precision showed an increased facilitatory priming effect for pseudoword targets preceded by pseudoword primes than those that followed word primes. People with high orthographic precision showed facilitatory form priming, irrespective of prime lexicality. This partially replicates the finding of Experiment 1, which showed a four-way interaction including these variables, though this was also moderated by NHD. The implications for these findings in relation to the LQH will be discussed in the General Discussion.

GENERAL DISCUSSION

Summary of findings

The current study used a suite of individual difference measures to assess which facets of LQH modulate lexical retrieval in production. In order to investigate competition resolution during visual word (Experiment 1) and pseudoword (Experiment 2) naming, we manipulated NHD and prime and target lexicality in a masked form priming experiment. Different experimental variables but the same individual difference component predicted the magnitude of the priming effect in both experiments. For word targets, we observed an interaction of orthographic precision, NHD, prime lexicality and relatedness. People with higher orthographic precision showed facilitatory form priming, irrespective of prime lexicality or NHD. For participants with lower orthographic precision, target words with sparse neighbourhoods preceded by pseudoword primes showed a larger facilitatory form priming effect than those preceded by word primes. The opposite was found for word targets from dense neighbourhoods. For pseudoword targets, we showed an interaction of orthographic precision, relatedness and prime lexicality. There was decreasing facilitatory priming for target pseudowords preceded by pseudoword primes with increasing orthographic precision. The converse was demonstrated for pseudoword targets that followed word primes.

For word and pseudoword targets, we showed that targets with a dense neighbourhood showed smaller facilitatory priming than those with a sparse neighbourhood. Interestingly, the current findings for NHD and relatedness shown for word and pseudoword targets are counter to Forster and Davis' (1991) results. Forster and Davis asked participants to name word targets from dense and sparse neighbourhoods preceded by a pseudoword prime in the related condition (e.g. *gord-GOLD*) and a word prime in the unrelated condition (e.g. *soil-GOLD*). The authors found that facilitatory form priming was stronger in word targets from dense than sparse neighbourhoods. It is unclear exactly why our results differ from theirs, though one notable difference is the number of participants in both studies (N=84 in our experiments, N=16 in Forster and Davis). In addition, we controlled for orthographic, phonological, and phonographic NHD, while Forster and Davis only controlled for orthographic NHD. As discussed in the Introduction, Adelman and Brown (2007) found that phonographic neighbours, not solely orthographic or phonological neighbours, predicts the naming latencies for word targets.

For pseudoword targets, people with high phonological precision showed larger facilitatory form priming than people with low phonological precision. This supports findings of Shapiro, Carroll and Solity (2013) and Moll, Fussenegger, Willburger and Landerl (2009), who argued that measures of reading fluency and phonological processing reflect the automaticity of grapheme-phoneme conversion. Participants with high phonological precision have redundant mapping between orthography and phonology, enabling them to dedicate more resources to other processes, such as articulation. Participants with low phonological precision expend more resources to grapheme-phoneme correspondence, leading to more co-activation of several candidates. This produces several possible pronunciations, which slows the processing of the pseudoword target and therefore can eliminate the priming effect (Timmer, Vahid-Gharavi & Schiller, 2012).

The role of LQH in masked priming for word and pseudoword targets

We found that visual word naming and visual pseudoword naming produced similar patterns of effects. One exception was that NHD interacted with relatedness, prime lexicality and orthographic precision for word naming, but not for pseudoword naming. Overall, the findings are in line with the LQH, which states that people with high orthographic precision possess detailed orthographic representations as well as phonological decoding (Share, 1995; Ziegler & Goswami, 2005), equipping them with improved word reading abilities due to increased reading experience. As a result of increased reading experience, people with high orthographic precision are more likely to quickly and efficiently retrieve lexical representations with minimal interference from neighbours. In turn, the lexical route is more likely to be used in people with high orthographic precision.

In addition, the findings for people with low orthographic precision are in line with the LQH, as these individuals are more likely to have less fluent phonological recoding due to limited and reduced print exposure (Castles, Rastle & Nation, 2018) and take longer to access the information that pertains to the lexical representation of the word. The neighbours of the item would therefore not be completely suppressed and can therefore aid lexical retrieval of the target. According to a dual-route model, Andrews (1997) argued that word targets with dense neighbourhoods are more likely to be strongly encoded, since they share similar neighbours to those in the mental lexicon. It could be extrapolated that word targets with dense neighbourhoods could strengthen the poor phonological recoding for people with low orthographic precision. In turn, lexical retrieval is accelerated and more frequent use of the lexical route is encouraged (Andrews, 1997). Word targets with sparse neighbourhoods do not share the same benefits as those with dense neighbourhoods, as there are few neighbours to strengthen the consolidation of the representation. For people with low orthographic precision, phonological recoding is not improved by the presence of very few neighbours, leading to laborious and slow lexical retrieval; thus, the non-lexical route is expended more often as opposed to the lexical route (Perfetti, 2007).

A possible explanation for the pseudoword target following the pseudoword prime is that pseudowords are processed at the sublexical level. Once the pseudoword target appears, the processing of the pseudoword target benefits from the sublexical overlap with the pseudoword prime, leading to facilitatory priming (Davis & Lupker, 2006). The magnitude of facilitatory priming for pseudoword targets preceded by word primes differs between people with high and low orthographic precision. People with low orthographic precision process the word prime more slowly. The result of slow access to the word prime is limited suppression of its neighbouring candidates. When the pseudoword target appears, recognition is aided by the sublexical overlap between the prime and target, resulting in a equal degree of facilitatory priming for participants with high or low orthographic precision. For people with high orthographic precision, we found that the presence of a prime word resulted in greater facilitation than when a pseudoword prime had been presented. One possible explanation for the word-pseudoword priming effect in this group is that during the processing of the prime word, its neighbours will be easily suppressed. When the pseudoword target is presented, it will not only benefit from the overlap at the sublexical level, but also from a stronger links between the orthographic, semantic, and phonological output representations of the word prime. These links, which can be partially exploited by the orthographically and phonologically related pseudoword targets, can give an extra boost during the recognition of the target (cf. Harm & Seidenberg, 2004), resulting in greater facilitation. This is consistent with previous studies that have shown that children are more likely to learn phonological forms when presented with orthographic-semantic information, by strengthening the link between the orthographic representation of familiar words and the pronunciation of a pseudoword (Ricketts, Bishop & Nation, 2009).

In addition, the current study showed that the priming effects for word targets depended on the component of orthographic precision. This contrasts with what we found for visual word recognition (Elsherif et al., under review), where a component involving phonological precision, as opposed to orthographic precision, modulated the priming effects. These findings for visual word naming and visual word recognition might seem counterintuitive, as one would assume that phonology would contribute strongly to visual word naming, whereas orthographic processes would drive the priming effect in visual word recognition. However, we propose that this pattern is related to the different stages of word recognition being assessed in naming and LDT. As stated in the introduction, eye-tracking studies have shown that early processing measures are more strongly correlated with naming times than lexical decision times, while later measures are more strongly related to lexical decision times than naming latencies (Schilling et al., 1998). These findings indicate that the LDT focuses primarily on the lexical processes of visual word recognition, while naming assesses the pre-lexical mechanisms of visual word recognition. In this sense, our findings suggest that the phonological effects (i.e. both access to phonology and phonological processing) occur around the end of the pre-lexical and beginning of the lexical stage, whereas orthographic processing occurs during the pre-lexical stages of lexical retrieval. The current findings are in line with Grainger, Kiyonaga and Holcomb (2006), who showed that phonology starts to have an influence in visual word recognition at 250ms and modulates performance around 400ms, while orthography already appeared around 200ms. They concluded that orthography arises earlier than phonology, thus highlighting that orthography occurs at the pre-lexical stage, while phonological processing occurs at the lexical stages of lexical retrieval.

The present results and the findings of Grainger et al. (2006) are compatible with Grainger and Holcomb's (2009) bi-interactive activation model, which posits that a printed word stimulus activates a set of perceptual features which, in turn, activate sublexical orthographic codes. The sublexical orthography sends activation not only to whole-word orthographic representation but also to the sublexical phonological representations. The sublexical orthography transverses the grapheme-phoneme interface to activate sublexical phonology. Finally, orthographic processing and phonological processing converge on the lexical-orthographic representations, and from there on to appropriate semantic representations. Both orthographic and phonological precision produce activation in the lexical representation of the items, though with orthographic information used somewhat earlier than phonological information (see also Frisson, Bélanger, & Rayner, 2014).

Taken together, our findings indicate that high orthographic precision equates to a robust lexical-orthographic representation. This results in the efficient suppression of neighbouring candidates of words - speeding lexical retrieval. In addition, the priming effects for visual word naming can be located in the pre-lexical stages of lexical retrieval, as demonstrated in both word targets and pseudoword targets. In this sense, our results extend the findings of Andrews and Hersch (2010), as we found that lexical retrieval is driven by orthographic precision for reading aloud and phonological precision for silent reading. Most importantly, redundancy and lexical precision are inter-linked. Put simply, the higher the level of orthographic precision, the more strongly bonded the properties of letter-sound correspondence, leading to a greater reliance on the direct access route to lexical representation and, in turn, faster lexical retrieval.

Conclusion

To conclude, orthographic precision moderates the priming effect in visual word naming and visual pseudoword naming. The same pattern of findings is shown for both words and pseudowords, but NHD only affects naming latencies for words. The results have important implications for the individual differences that underlie visual word production. In addition, they contribute to the development of theoretical models that underlie visual word recognition and its time-course. The goal of establishing a link between empirical data concerning individual differences in adult skilled readers and models of skilled reading may shed light on reading ability and further our understanding of fundamental aspects of the adult word recognition system.

CHAPTER 4.

LEXICAL PRECISION FOR WORD RECOGNITION IN ADULTS WITH DYSLEXIA

ABSTRACT

In Chapters 2 and 3, we demonstrated that phonological precision and orthographic precision contributed to the priming effects in the lexical decision task and word naming task, respectively. In this study, we sought to assess whether people with dyslexia (PWD) would demonstrate a similar pattern to people with low phonological and low orthographic precision. Fifty PWD had to recognise or produce word and pseudoword targets with dense and sparse neighbourhoods in a masked form priming experiment. In addition, several individual difference measures of language and cognitive processes were collected, and a principal component analysis was used to group these data into factors. Using a lexical decision task (Experiment 1), we found that form priming of word targets was moderated by a factor linked to lexical precision. People with low lexical precision showed little, if any, priming effects. Dyslexic individuals with high lexical precision demonstrated inhibitory priming for word targets with dense neighbourhoods. Inhibitory priming was shown for word targets with sparse neighbourhoods following word primes and facilitatory priming for those preceded by pseudoword primes. For pseudoword targets, an overall facilitatory priming effect was shown for dyslexic individuals with low lexical precision and little, if any, priming effects for those with high lexical precision. Using word and pseudoword naming (Experiments 2 and 3), the component of lexical precision did not moderate form priming. These results indicate that people with dyslexia have intact lexical representation, while they possess an orthographic precision impairment at the sublexical level.

Keywords: Lexical Quality Hypothesis; visual word recognition; visual word production; lexical precision; dyslexia

INTRODUCTION

In Chapters 2 and 3, we found that for neurotypical participants a component related to phonological precision affected the priming effect in the LDT while a component related to orthographic precision modified the priming effect in word naming. In the LDT, people with high phonological precision showed inhibitory priming for word targets with dense neighbourhoods, whereas they demonstrated facilitatory priming for word targets with sparse neighbourhoods. In visual word naming, people with high orthographic precision demonstrated only facilitatory priming, which was smaller than the facilitatory priming shown in people with low orthographic precision. People with low orthographic precision demonstrated larger facilitatory priming effects for word targets with dense neighbourhoods than those with sparse neighbourhoods. Together, these results indicate that people with good phonological and orthographic precision face less competition between the prime and its neighbours, including the target, allowing them direct access to the mental lexicon. In turn, once the target appears, lexical competition between prime and target ensues (Davis & Lupker, 2006). However, this may not generalise to people with dyslexia (PWD), who have poor orthographic and phonological representations (see review by Bishop & Snowling, 2004). The aim of Chapter 4 was therefore to investigate whether PWD would demonstrate a similar pattern to people with low phonological and orthographic precision or show an individual difference pattern matching that of the neurotypical population in Chapters 2 and 3.

Developmental dyslexia is a specific learning difficulty that has a genetic basis and adversely influences reading acquisition, irrespective of adequate intelligence, educational opportunity and socio-economic background (Snowling, 2000). Dyslexia manifests itself in 7-10% of the population and persists throughout life (Peterson & Pennington, 2010). Arguably, the key problems are difficulties in phonological awareness, short-term memory and verbal processing speed (see reviews by Bishop & Snowling, 2004; Melby-Lervag, Lyster & Hulme, 2012). The main hypothesis to explain the difficulties is that dyslexia results from deficient phonological representations leading to an inefficient connection of sounds to letters (e.g. Snowling, 1981). This impairment leads to a poor build-up of the orthographic lexicon necessary for fluent reading and word learning (Ehri, 2005; Share, 1995). These phonological and orthographic impairments persevere into adulthood (e.g. Bishop & Snowling, 2004; Bruck, 1990). According to the LQH (Perfetti, 2007), these difficulties lead to slower processing of words and pseudowords increasing the time taken to match graphemes to phonemes. This leads the majority of resources for PWD being dedicated to grapheme-phoneme conversion (i.e. letter-sound rules), thereby negatively impacting resources for higher-level (e.g. semantic) processes. As a result of the lack of resources for higher-level processes, PWD take longer to recognise, produce and discriminate between words and pseudowords. Put simply, the grapheme-phoneme conversion is not completed automatically, and the one-to-one mapping between grapheme and phoneme is laborious and slow (Ehri, 2005).

Relative to the neurotypical population, the relationship between form priming and NHD for PWD has received little, if any, attention, except in one study that indirectly assessed the development of orthographic precision in word targets with dense neighbourhoods (Lete & Fayol, 2013). Lete and Fayol tested 52 third graders (*M* = 8 years and 11 months), 55 fifth graders (*M* = 10 years and 11 months), 16 adolescents with dyslexia (*M* = 13 years and 1 month), and 24 university students (*M* = 26 years and 11 months) and gave them an LDT consisting of 27 five-letter word targets on a computer screen. Each target (e.g. TABLE) was preceded by a pseudoword form prime (e.g. lable), a pseudoword transposed prime (e.g. atble) or a non-word control prime (e.g. ubcmf). The authors found that there was no form priming for adults and third graders. However, adolescents with dyslexia and fifth graders showed facilitatory form priming, albeit with a trend for adolescents with dyslexia showing a larger facilitatory priming effect compared to the other groups. An interpretation of this finding for the lack of priming effects in third graders is that although French is an opaque language, it is more transparent than English. Phonological coding is therefore likely to be used during this period, while orthographic processing is mastered later, around fifth grade, thus demonstrating facilitatory form priming (Lete & Fayol, 2013). In contrast to third graders and fifth graders, with increasing lexical precision, adults need a closer match between primes and targets to experience facilitation. This is consistent with Ziegler and Goswami (2005), who argued that children with dyslexia do not perform worse than children matched on reading-age during tasks that need automatic orthographic access to whole words. However, they do show deficits in relation to sublexical phonology. It could be concluded that PWD are therefore more likely to depend on a direct lexical or orthographic-to-semantic strategy for word reading (Nobre & DeSalle, 2016). This indicates that children with dyslexia do not need to use sublexical processes to recognise words but use direct lexical access. In addition, children with dyslexia can develop a mature orthographic representation to compensate for the sublexical deficit.

Although it could be argued that PWD may behave similarly to less skilled readers such that the sublexical route is heavily used, evidence has shown that PWD are more likely to use the lexical route if they have a large vocabulary (Hanley, 1997). Hanley gave PWD a suite of individual difference measures to assess the role of vocabulary and picture naming on irregular word reading and nonword reading. The author found that PWD with larger vocabulary scores and faster picture naming performed better than those with low vocabulary scores in irregular word reading, but there was no group difference for nonword reading. They concluded that PWD with high vocabulary scores are more likely to use the lexical, as opposed to the non-lexical, reading route. At face value, PWD do not differ from controls in terms of the lexical route being used but their underlying reason for using the lexical route differs. People with dyslexia use the lexical route to compensate for their impaired sublexical processes, whereas more skilled readers have fully automatized sublexical reading abilities that allow them to access the direct lexical route easily (Perfetti, 2007, 2017).

In addition, a notable point from Hanley's (1997) study is that there are large inter-individual differences in PWD for reading. Using semantic priming (i.e. a semantically related prime and target are presented, e.g. nurse-DOCTOR), Van der Kleij, Groen, Segers and Verhoeven (2019) supported Hanley's findings that there are individual differences within the dyslexic population. Van der Kleij et al. found that PWD with higher word reading efficiency scores, as measured by the One Minute Test, had significantly stronger semantic priming effects, whereas people with no diagnosis of dyslexia showed no correlation between word reading scores and semantic priming effects. These results highlight that perhaps an individual difference approach is required to assess the underlying causes of dyslexia. This raises an additional problem, if there are large individual differences in PWD, then more skilled PWD are better at reading than their less-skilled counterparts in the following: vocabulary knowledge, reading comprehension and phonological processing (see review by Huettig, Lachmann, Reis & Pettersson, 2018). Huettig et al. argued that previous mixed findings for phonological awareness resulted from varying levels of print exposure not being included. This makes it difficult to assess which component(s) of phonology, orthography and semantics modulate(s) lexical retrieval in PWD and competition resolution. It is therefore important to group these measures together to avoid collinearity, using a Principal Component Analysis (PCA) to form underlying factors to assess where the difficulties for PWD may occur.

In the study reported in this Chapter, individual differences have been shown to occur in PWD (van der Kleij et al., 2019). If this is the case, the same pattern of findings shown for the neurotypical population in Chapters 2 and 3 should be replicated. If it is not the case, and PWD have poor orthographic and phonological representations, we would expect that PWD would perform similarly to people with low phonological precision and low orthographic precision, as seen in Chapters 2 and 3.

METHOD

Participants

The same 84 participants from Chapters 2 and 3 were used as a control group for the current study (Elsherif, Wheeldon & Frisson, under review a, b and c). In addition, we recruited 50 PWD aged 19-32 years (28 women, 19 left-handers, mean age: 20.72, SD: 2.70) from the Universities of Birmingham, Warwick and Leicester All adult participants provided a diagnostic report of their dyslexia. The research was solely conducted at the University of Birmingham and was approved by the university's Ethics Committee (ERN_15-1236) and was aligned with the ethical guidelines of the British Psychological Society. The same exclusion criteria, sans diagnosis of dyslexia, were applied to the dyslexic population as were done for the neurotypical participants. For PWD, students were given university credits as compensation, whilst those from other universities received monetary compensation.

We conducted a power analysis based on Lete and Fayol's (2013) analysis of the interaction of relatedness and group, estimating Cohen's *d* to be 1.04 and 0.84[18]. Using G*Power 3.1.9.4 for

[18]The equation used to calculate partial eta was from Richardson (2011):

$$\eta^2 = \frac{(df1 * F)}{(df1 * F + df2)}$$

From Lete and Fayol's (2013) study, we inputted the following values in the equation: the numerator degrees of freedom (df1) was 1, the F-values for subjects and items were 10.22 and 5.75 respectively, plus the denominator degrees of freedom (df2) were 15 for within-subject and 26 for within-item.

$$0.21 = \frac{(1 * 10.22)}{(1 * 10.22 + 38)}$$

The partial eta (0.21 for within-subjects and 0.15 for within-items) was then transformed into Cohen's *d*, following the equation of Brysbaert and Stevens (2018):

paired *t*-test (Faul, Erdfelder, Buchner & Lang, 2009), it was approximated that 15 participants and 20 items produced sufficient power (β = 0.95). As we were interested to test a three-way interaction: relatedness, NHD and prime lexicality, we needed a minimum of 45 participants and 40 items in total. However, prior studies have been argued to be underpowered, thus more participants (*N* = 50) and target items (*N* = 80 words and 80 pseudowords) were tested in order to be more conservative (Button et al., 2013). The reasons we used general linear mixed models (GLMM) are detailed in Chapters 2 and 3. This increase in sample size, items and the use of GLMM allowed us to detect small effects, compared to Lete and Fayol (2013).

Our participants in general were relatively homogenous in their demographics, excluding gender and handedness (Table 4.1.). Education level was classified as A-levels (coded as 1), Bachelor's degree (coded as 2), Master's degree (coded as 3) and PhD (coded as 4). There were 43 undergraduate and 7 post-graduate students in the dyslexic population, while there were 83 undergraduate and 1 post-graduate student in the control population. The homogeneity of variance between groups was assessed with the Fligner Killeen test. The dyslexia and control groups did not differ significantly from each other in terms of average education level ($t(77.27)=-1.86$, $p=.07$), bilingualism ($t(132)=-1.86$, $p=.07$) or age ($t(57.80)=-1.36$, $p=.18$), but there were significantly more males ($t(67.10)=-5.90$, $p<.001$) and left-handed individuals ($t(89.37)=-3.30$, $p=.001$) in the dyslexia than in the control group. Surprisingly, 17 out of 50 people with dyslexia (i.e. 34%) had recovered from childhood stuttering (Elsherif et al., under review c). The majority (56%) of the participants were diagnosed with dyslexia aged 16 to 18, 20% of the participants

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$$d = \sqrt{\frac{(4 * \eta^2}{1 - \eta^2}}$$

Subsequently, we inputted the partial eta squared value to attain a Cohen's *d* of 1.04 and 0.84 for subjects and items, respectively.

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were diagnosed below 16, and 24% above the age of 18. Descriptive statistics for the participant sample are shown in Table 4.1.

Table 4.1. The means and standard deviation for demographic variables for the two diagnostic groups.

	Controls (*N* = 84)	**Dyslexics (*N* = 50)**
	Mean (*SD*)	**Mean (*SD*)**
Age (year)	20.2 (1.03)	20.7 (2.7)
Gender (%female)	91.7 (0.28)	34.0 (0.50)
Handedness (%Right)	89.0 (0.41)	62.0 (0.49)
Bilingualism (%Bilingual)	0.0 (0)	4.0 (0.20)

Tests, materials and procedures

The same tests, materials and procedures from Chapters 2 and 3 were used for the current study.

RESULTS

Results from the individual difference measures can be found in Table 4.2. Participants with dyslexia performed worse on tasks that measured phonological processing, reading fluency and spelling than the neurotypical population (in line with previous findings, see review by Melby-Lervag et al., 2012). There was no group difference in the following measures: print exposure, naming and silent Stroop, reading comprehension, non-verbal intelligence, receptive and expressive vocabulary (Table 4.2). For descriptive and inferential statistics, see Elsherif et al. (under review c) for more details.

Table 4.2. Means and standard deviation of all measures for the control and dyslexic populations.

	Controls (*N* = 84)	Dyslexics (*N* = 50)	T value	Cohen's *d*
	Mean (*SD*)	Mean (*SD*)		
Author Recognition Test (out of 50)	15.07 (7.69)	16.54 (9.61)	$t(85.85^{a}) = -0.91$	-0.17
Title Recognition Test (out of 50)	18.48 (6.14)	19.76 (8.82)	$t(77.26^{a}) = -0.89$	-0.17
Magazine Recognition Test (out of 50)	11.20 (4.48)	11.02 (5.24)	$t(90.50^{a}) = 0.20$	0.04
British Picture Vocabulary Scale (out of 60)	42.74 (7.3)	42.4 (7.78)	$t(132) = 0.25$	0.04
Expressive Vocabulary Test (out of 118)	71.87 (8.01)	72.98 (10.36)	$t(132) = -0.69$	-0.12
TOWRE Sight Word Efficiency (out of 108)	87.34 (11.24)	78.82 (12.10)	$t(132) = 4.10^{***}$	0.73
TOWRE Phoneme Decoding (out of 65)	57.88 (5.56)	49.3 (7.15)	$t(132) = 7.21^{***}$	1.37
TIWRE (out of 25)	21.19 (1.86)	20.26 (2.25)	$t(132) = 2.56^{*}$	0.46
CTOPP Phoneme Elision (out of 20)	16.67 (2.38)	15.32 (3.04)	$t(84.36^{a}) = 2.66^{**}$	0.51
CTOPP Memory for Digits (out of 21)	16.65 (2.14)	14.34 (2.03)	$t(132) = 6.11^{***}$	1.09
CTOPP Non-Word Repetition (out of 18)	13.67 (1.73)	10.68 (2.23)	$t(132) = 8.63^{***}$	1.54
CTOPP Rapid Letter Naming (ms)	26.27 (4.79)	32.59 (9.42)	$t(132) = -5.10^{***}$	-0.91
CTOPP Phoneme Reversal (out of 18)	11.43 (2.62)	8.94 (2.49)	$t(132) = 5.37^{***}$	0.96
Gray Silent Reading (out of 30)	22.25 (3.33)	21.18 (4.05)	$t(132) = 1.64$	0.29
Raven's progressive matrices (out of 60)	45.48 (6.53)	47.38 (7.13)	$t(132) = -1.6$	-0.28
Spelling (out of 20)	16.49 (2.37)	13.24 (2.95)	$t(86.16^{a}) = 6.56^{***}$	1.24
Naming Stroop effect (IES)	190 (137)	213 (75)	$t(132) = -1.23$	-0.22
Manual Stroop effect (IES)	134 (97)	158 (105)	$t(132) = -1.84$	-0.33

Note. *t* values above 2 indicates significance. $^{*}p<.05$ $^{**}p<.01$ $^{***}p<.001$. ^{a} = homogeneity of variance is unequal, assessed by Fligner-Killeen test (Fligner-Killeen test of homogeneity of variances, n.d.).

We used the same approach to PCA as in Chapters 2 and 3. In accordance *a priori* predictions, we calculated composite scores based on the 15 variables used in the current study. The composite scores were calculated as follows. A standard score for vocabulary (ZVocab) was formed as the two vocabulary measures were highly correlated (i.e. EVT and BPVS; *r* = .54), providing a detailed measure of vocabulary ability. In addition, a composite measure of phonological working memory (ZMemory) was calculated because of two moderately correlated measures of phonological working memory (i.e. nonword repetition and memory for digits; *r* = .33). In addition, a standard measure of print exposure (ZPrintExposure) was obtained from the two highly correlated measures of print exposure (ART and TRT; *r* = .85). Finally, three measures of reading fluency were averaged to form a representative measure of reading fluency (ZReadingFluency), as they were moderately-to-highly correlated (*r* = .32 for TOWRE word reading and Rapid Letter Naming; *r* = .41 for TOWRE phonemic decoding and Rapid Letter Naming and *r* =

.58 for TOWRE word reading and phonemic decoding). In order to explore the relationship between orthographic, phonological and semantic measures, Pearson correlation coefficients were calculated (Table 4.3.). Examination of these relationships indicated that the standardised measure of print exposure was highly correlated with spelling and the standard vocabulary score (e.g. Burt & Fury, 2000; Martin-Chang & Gould, 2008). Importantly, the degree of collinearity between these measures was above .3, indicating that these measures may share a common underlying process. A multi-variate approach, such as PCA, was therefore appropriate.

Table 4.3. Correlations between tasks (dyslexics: above the diagonal; control: below the diagonal)

	ZVocab	PE	ZMemory	ZRF	PR	TIWRE	Spell	GSRT	ZPE
ZVocab		-0.02	0.23	0.26^{+}	0.13	0.54***	0.28^{+}	0.63***	0.69***
PE	0.16		-0.03	0.03	0.28^{+}	0.13	0.11	0.02	-0.12
ZMemory	0.23*	-0.01		0.03	0.17	0.27^{+}	0.16	0.30*	0.27^{+}
ZRF	0.10	-0.02	0.26*		0.17	0.02	0.08	0.28^{+}	0.20
PR	0.32**	0.18^{+}	0.31**	0.19^{+}		0.22	0.15	0.09	0.04
TIWRE	0.25*	0.18^{+}	0.22*	0.31**	0.42***		0.51***	0.42**	0.56***
Spell	0.37***	0.10	0.04	0.24*	0.27*	0.36**		0.25	0.25
GSRT	0.38***	0.28**	0.04	-0.08	0.24*	0.22*	0.06		0.54***
ZPE	0.35***	0.07	0.13	0.02	0.15	0.24*	0.43**	0.23*	

Note. Standard vocabulary composite measure (ZVocab), Phoneme Elision (PE), Standard phonological working memory composite measure (ZMemory), Standard reading fluency composite measure (ZRF), Phoneme Reversal (PR), Gray Silent Reading Test (GSRT), Test of Irregular Word Reading Efficiency (TIWRE), Standard print exposure composite measure (ZPE). $^{+}p < .10$, $^{*}p < .05$, $^{**}p < .01$ and $^{***}p < .001$.

Principal component analysis

The PCA was computed in the same way as in Chapters 2 and 3 (see Appendix D for the PCA with the individual difference measures included as separate, as opposed to combined, measures). Three variables were removed from the analysis, as their correlation coefficient was below .3 (i.e. ZRF, phoneme reversal and phoneme elision). The Kaiser-Meyer-Olkin measure of sampling adequacy was .79, above the commonly recommended value of .50 (Field, 2009). The Bartlett's test of sphericity was significant ($\chi 2$ (15) =95.97, $p < .001$), indicating that the remaining six variables were appropriate for the PCA. The initial analysis yielded one factor with an eigenvalue greater than Kaiser's criterion of 1. A varimax rotation was performed as there was only one factor. Variables with loadings above 0.45 were considered and are listed in terms of individual loading factor in Table 4.4.

The factor includes the composite measures of print exposure, vocabulary, phonological working memory, together with irregular word reading, reading comprehension and spelling (all positive loadings). The positive loadings of these measures indicate that this factor denotes a construct of **lexical precision**. This factor could be posited to reflect the direct access to, strength and coherent nature of, the lexical representation.

Table 4.4. Factor produced by the PCA in the dyslexic population.

Factor 1 Lexical precision	Loading value
Zvocab	0.85
Zprintexposure	0.81
TIWRE	0.79
GSRT	0.65
Spelling	0.63
Zmemory	0.46
% variance	*0.51*
Cumulative variance	*0.51*

Note. Standard vocabulary composite measure (ZVocab), Standard phonological working memory composite measure (ZMemory), Standard reading fluency composite measure (ZRF), Gray Silent Reading Test (GSRT), Test of Irregular Word Reading Efficiency (TIWRE) and Standard print exposure composite measure (ZPE).

General Linear Mixed Effect model (GLMM)

The same analyses and outlier rejection used in Chapters 2 and 3 were employed for the current chapter. The factor of lexical precision was included in the model as a fixed effect and analysed as continuous variable. The lexical precision factor was centred. The priming was calculated as the related prime condition subtracted from the unrelated prime condition. Following this subtraction, positive values were indicative of facilitation, whereas inhibitory priming was analogous to negative values. Following any interactions with the lexical precision factor, a median split was used to categorise the lexical precision factor into a binary variable (high vs. low) to allow the number of data points to be matched equally. Accuracy was high for all conditions, with only minute priming effects. Since none of the models using accuracy data reached convergence, we will not discuss accuracy further in any of the tasks.

Word targets in the LDT

Six word items (i.e. BARD, BIDE, BOLL, CRAG, FLAN and NOOK) produced more than 50% of errors and were removed from the analyses, leaving 34 target words per condition. In total, 18.3% of the data were removed prior to the analyses due to errors made, slow and fast reaction times. Average RTs, SDs and the proportion of correct responses for each condition are shown in Table 4.5. The model for the lexical decision for word targets did not converge until the item slope was removed, leaving only an item intercept, and the three-way interaction was reduced to NHD as an individual factor in the random structure (see appendix E for the final model code for word target and pseudoword target). The output of this model is shown in Table 4.6.

Table 4.5. Mean response times and proportion correct for each prime lexicality, relatedness and NHD condition in the dyslexic population.

	Word Target				Pseudoword target			
	High N		Low N		High N		Low N	
Prime lexicality	Word Prime	Nonword prime	Word Prime	Nonword prime	Word Prime	Nonword prime	Word Prime	Nonword prime
Related								
RT	648(156)	649(165)	662(168)	650(172)	736(190)	739(194)	683(168)	685(173)
P correct	.93(0.25)	.90(0.28)	.90(0.31)	.91(0.28)	.88(0.32)	.86(0.35)	.94(0.25)	.92(0.27)
Unrelated								
RT	647(149)	647(155)	660(160)	663(150)	738(181)	752(190)	630(174)	696(178)
P correct	.92(0.27)	.94(0.28)	.89(0.32)	.91(0.29)	.87(0.34)	.87(0.34)	.95(0.26)	.93(0.26)
Priming effect								
RT	-1	-2	-2	13	-2	13	-4	11
P correct	-.01	.04	-.01	.00	.01	.01	-.01	-.01

Note. Response times (RT); Proportion (P); Response times are measured in milliseconds and standard deviations are in parentheses.

Table 4.6. The minimal model output for RTs for word target in dyslexic population.

Fixed Effects	Estimate	Std. Error	95% LCI	95% UCI	*t* values
(Intercept)	6.45300	0.01977	6.414172	6.491828	326.38
Priming conditions					
NHD	-0.00021	0.01793	-0.035455	0.034791	-0.01
Relatedness	-0.00040	0.00936	-0.018521	0.018049	-0.04
Prime lexicality	0.00133	0.00936	-0.016882	0.019782	0.14
Individual Factors					
Lexical precision	-0.00489	0.01531	-0.031339	0.028677	-0.3
Interactions					
NHD * relatedness	0.02639	0.01327	-0.000080	0.0518996	1.99*
NHD * prime lexicality	0.01835	0.01331	-0.007978	0.0441580	1.38
Prime lexicality * relatedness	0.00058	0.01319	-0.025431	0.0262348	0.04
Lexical precision * NHD	-0.01482	0.01014	-0.037175	0.0017548	-1.46
Lexical precision * prime lexicality	-0.00095	0.00988	-0.021572	0.0164164	-0.10
Lexical precision * relatedness	-0.02639	0.00965	-0.029382	0.0081012	-1.76**.**
NHD * prime lexicality * relatedness	-0.02440	0.01883	-0.028088	-0.020711	-1.34
Lexical precision * NHD * prime lexicality	0.02329	0.01401	0.006310	0.060250	1.66**.**
Lexical precision * NHD * relatedness	0.03210	0.01372	-0.006367	0.046867	2.34*
Lexical precision * prime lexicality * relatedness	-0.02519	0.01376	-0.051154	0.002354	1.63
Lexical precision * NHD * relatedness * prime lexicality	-0.05722	0.01961	-0.102672	-0.026388	-2.92*

Note. * *p*<.05 and **.***p*<.10.

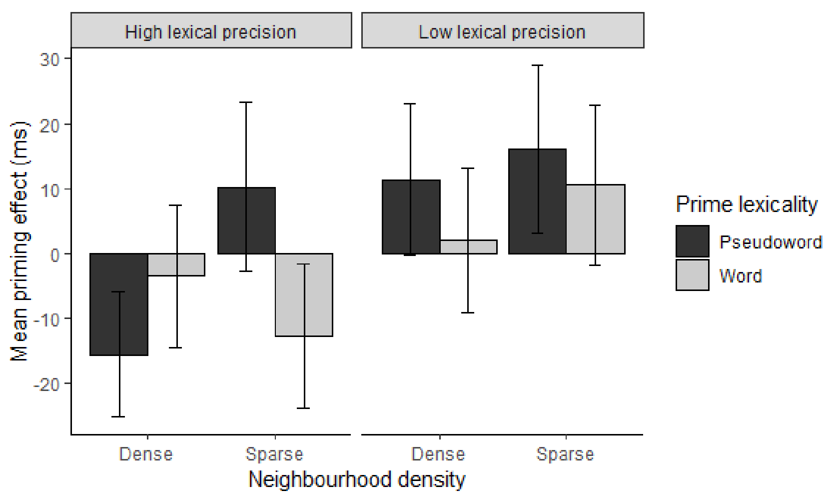

Figure 4.1. Reaction time (RT) priming effects (in ms) for high- and low-N targets, word and pseudoword primes and separated by the lexical precision composite in dyslexic population. Positive priming effects reflect facilitation for targets preceded by related primes, relative to unrelated primes. Negative priming effects reflect inhibition for targets preceded by related primes, compared to unrelated primes. Error bars represents 95% confidence interval for each condition.

In the full model, there was a significant four-way interaction between lexical precision, NHD, relatedness and prime lexicality (see Figure 4.1.). Dyslexic individuals with high lexical precision were more likely to show facilitatory priming for target words with sparse neighbourhoods preceded by pseudoword primes and inhibitory priming for those with sparse neighbourhoods that followed word primes. Dyslexic individuals with low lexical precision were more likely to demonstrate facilitatory priming and did not show inhibitory priming for any of the conditions. The full model was split into two sub-models: high lexical precision and low lexical precision. Lexical precision was removed from the equation and the same procedures from the full model for the analysis and random structure were applied to the sub-models. In the high lexical precision sub-model, the NHD, prime lexicality and relatedness interaction were significant (b = -0.053, t = -2.10, p = .04). Dyslexic individuals with high lexical precision were more likely to demonstrate increased facilitatory priming for target words with sparse neighbourhoods preceded by pseudoword primes, whilst they showed inhibitory priming for those preceded by word primes. For dyslexic individuals with low lexical precision, no interaction between NHD, prime lexicality and relatedness was shown (b = 0.003, t = 0.13, p = .90), no interactions of NHD and prime lexicality (b = -0.006, t = 0.36, p = .72), NHD and relatedness (b = 0.013, t = 0.69, p = .49), together with prime lexicality and relatedness (b = -0.012, t = -0.65, p = .51) were observed. In addition, no simple effects of NHD (b = -0.002, t = -0.10, p = .92), relatedness (b = 0.01, t = 1.10, p = .27) and prime lexicality (b = -0.004, t = 0.30, p = .77) were evident. Dyslexic individuals with low lexical precision showed facilitatory priming effects for word targets but this was not significant.

The sub-model for high lexical precision was split according to NHD: dense and sparse. NHD was removed from the equation and random structure, and the same analyses from the full model were applied to the sub-models. For PWD with high lexical precision, an interaction between prime lexicality and relatedness was demonstrated for target words with sparse neighbourhoods (*b* = -0.039, *t* = -2.13, *p* = .03), but not for target words with dense neighbourhood (*b* = 0.014, *t* = 0.78, *p* = .44). For dense neighbourhoods, no simple effects of prime lexicality (*b* = -0.0007, *t* = -0.06, *p* = .96), nor relatedness were shown (*b* = -0.015, *t* = -1.22, *p* = .22). Dyslexic individuals with high lexical precision showed increased facilitatory priming for target words with sparse neighbourhoods preceded by pseudoword primes, whilst inhibitory priming was observed for those preceded by word primes.

The sub-model for sparse neighbourhoods for dyslexic individuals with high lexical precision was further split according to prime lexicality: word prime and pseudoword prime. Prime lexicality was removed from the equation and random structure, and the same analyses from the full model were applied to the sub-models. A simple effect of relatedness was not significantly observed for word targets that followed word primes (*b* = -0.01, *t* = -1.2, *p* = .23, *d* = -0.07) in dyslexic individuals with low lexical precision who responded to sparse neighbourhoods, while the relatedness effect in word targets preceding pseudoword primes approached significance (*b* = 0.02, *t* = 1.87, *p* = .06, *d* = 0.11). Dyslexic individuals with high lexical precision were more likely to demonstrate increased facilitatory priming effects for target words with sparse neighbourhoods preceded by pseudoword primes.

Word targets in word naming

The same analysis of the PCA and GLMM from Experiment 1 were used. The naming latencies for each participant in each condition were trimmed in a similar way to the LDT analysis. In addition, one word item (i.e. BASS) produced more than 50% errors, and was removed from the word naming analysis, leaving 39 target words per condition. In total, the outlier rejection, removal of this item and errors resulted in 5.4% of the data being removed. Average RTs, SDs, and the proportion of correct responses for each condition are shown in Table 4.7. The priming effects concerning naming latencies were facilitatory for word targets and priming effects were smaller for words with dense neighbourhoods than those with sparse neighbourhoods. The model for word naming did not converge until the item slope was removed, leaving only a random item intercept. The three-way interaction was reduced to NHD as an individual factor in the random structure for the subject (see appendix E for the final model code for LDT, word naming and pseudoword naming). The output of this model is shown in Table 4.8.

Table 4.7. Mean naming latencies and proportion correct each prime lexicality, relatedness and NHD condition for word targets in the dyslexic population.

	High N		Low N	
Prime lexicality	Word Prime	Nonword prime	Word Prime	Nonword prime
Related				
RT	506 (134)	513 (124)	500(131)	497 (122)
P correct	.93(0.25)	.90 (0.30)	.998(0.05)	.90 (0.31)
Unrelated				
RT	515(119)	522 (126)	516(124)	518 (127)
P correct	.92 (0.27)	.94 (0.25)	.992(0.09)	.89 (0.32)
Priming effect				
RT	9	9	16	21
P correct	-.01	.04	-.01	.00

Note. Response times (RT); Proportion (P); Response times are measured in milliseconds and standard deviations are in parentheses

Table 4.8. The minimal model output for naming latencies for word target in dyslexic population.

Fixed Effects	Estimate	Std. Error	95% LCI	95% UCI	*t* values
(Intercept)	6.21200	0.02121	6.170423	6.25357	280.28
Priming conditions					
NHD	-0.03270	0.01385	-0.05985	-0.00555	-2.36*
Relatedness	0.02040	0.00578	0.00907	0.03173	3.53*
Prime lexicality	-0.01657	0.00578	-0.02790	-0.00524	-2.87*
Individual Factors					
Lexical precision	-0.04720	0.02034	-0.08707	-0.00733	-2.32*
Interactions					
NHD * relatedness	0.02039	0.00810	0.00451	0.03627	2.52*
NHD * prime lexicality	0.01631	0.00810	0.00043	0.03219	2.01*

Note. * $p<.05$

The full model produced a significant interaction of NHD and prime lexicality (Table 4.8.). Participants produced shorter naming latencies for word targets with dense neighbourhoods that were preceded by word primes than those following pseudoword primes. There was no difference on naming latencies in word targets with sparse neighbourhoods that followed word primes and those that were preceded by pseudoword primes. The full model was split into two sub-models: dense and sparse neighbourhoods. NHD was removed from the equation and the same procedures for the analyses from the full model were applied to the submodel. An effect of prime lexicality was shown for word targets with dense neighbourhoods (b = -0.02, t = -2.87, p = .004, d = -0.07) but not word targets with sparse neighbourhoods (b = -0.0003, t = -0.05, p = .96, d = -0.001). For word targets with dense neighbourhoods, word targets that followed word primes resulted in shorter naming latencies (M = 511, SE = 2.94) than those preceding a pseudoword prime (M = 518, SE = 2.90). For word targets with sparse neighbourhoods, there was no significant difference for word targets preceded by word primes (M = 508, SE = 2.92) and pseudoword primes (M = 508, SE = 2.84).

The full model produced a significant interaction of NHD and relatedness (Table 4.8.). Participants showed smaller facilitatory priming effects in word targets with dense neighbourhoods than those with sparse neighbourhoods. The full model was split into two sub-models: dense and sparse neighbourhoods. NHD was removed from the equation and the same procedures for the analyses from the full model were applied to the submodel. An effect of relatedness was shown for word targets with dense neighbourhoods ($b = 0.02$, $t = 3.56$, $p < .001$, $d = 0.09$) and sparse neighbourhoods ($b = 0.04$, $t = 7.15$, $p < .001$, $d = 0.17$). Word targets with dense neighbourhoods and sparse neighbourhoods showed facilitatory priming. However, the priming effect was larger in word targets with sparse neighbourhoods than those with dense neighbourhoods.

With regard to the individual factors, the model output showed that there was a significant effect of lexical precision on log RT. Unsurprisingly, the higher the components of lexical precision, the shorter the reaction times.

Pseudoword targets in the LDT

The same trim from word targets was applied to pseudoword targets. Three pseudoword items (i.e. BEED, TASE and WALE) produced more than 50% errors and were therefore removed from the lexical decision analyses, leaving 37 target pseudowords per condition. The trim and removal of items resulted in the loss of 15.3% of the data. Average RTs, SDs and proportion correct of reaction times for each condition, are shown in Table 4.5. The model for the lexical decision focusing on the pseudoword target did not converge until the item-slope was removed, leaving only an item-intercept, and the three-way interaction for subjects was reduced to NHD by itself in the random structure. The minimal model output is shown in Table 4.9.

Table 4.9. The minimal model output for RTs for pseudoword target in dyslexic population.

Fixed Effects	Estimate	Std. Error	95% LCI	95% UCI	*t* values
(Intercept)	6.5840	0.02073	6.543683	6.624317	317.69
Priming conditions					
NHD	-0.0769	0.01911	-0.097992	-0.055028	-4.02*
Relatedness	0.0163	0.01098	-0.004753	0.038053	1.49
Prime lexicality	-0.0075	0.01094	-0.028132	0.014832	-0.68
Individual Factors					
Lexical precision	-0.0043	0.01754	-0.036688	0.032068	0.24
Interactions					
NHD * relatedness	-0.0035	0.01497	-0.030160	0.021820	-0.24
NHD * prime lexicality	0.0056	0.01500	-0.021938	0.030198	0.37
Prime lexicality * relatedness	-0.0995	0.01552	-0.036253	0.015413	-0.64
Lexical precision * NHD	0.0199	0.01181	-0.015613	0.042913	1.69.
Lexical precision * prime lexicality	0.0091	0.01135	-0.017601	0.041081	0.80
Lexical precision * relatedness	0.0451	0.01132	-0.004250	0.056510	0.04
NHD * prime lexicality * relatedness	0.0018	0.02120	0.007408	0.037552	2.05*
Lexical precision * NHD * prime lexicality	-0.0303	0.01557	-0.022754	-0.001546	-1.94.
Lexical precision * NHD * relatedness	-0.0311	0.01545	-0.032124	-0.010916	-2.01*
Lexical precision * prime lexicality * relatedness	-0.0130	0.01594	-0.072000	-0.026880	-0.82
Lexical precision * NHD * relatedness * prime lexicality	-0.0461	0.02186	-0.073410	-0.029790	2.11*

Note. * *p*<.05.

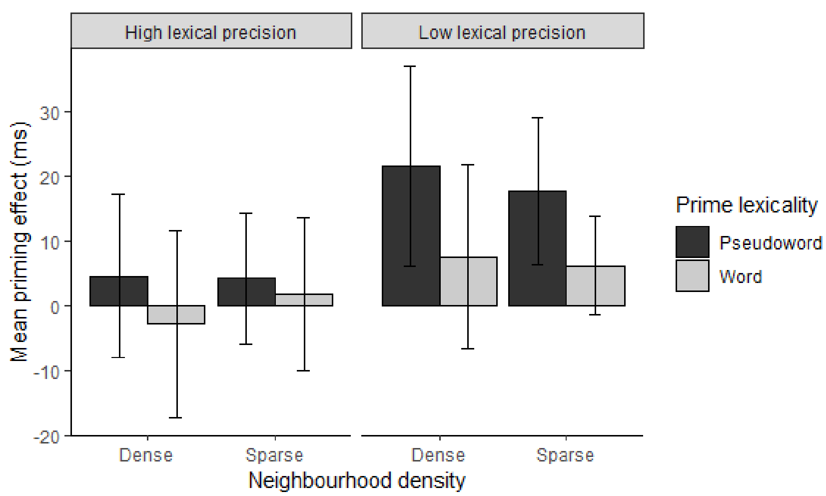

Figure 4.2. Reaction time (RT) priming effects (in ms) for high- and low-N targets, word and pseudoword primes and separated by the lexical precision composite in dyslexic population. Positive priming effects reflect facilitation for targets preceded by related primes, relative to unrelated primes. Error bars represents 95% confidence interval for each condition.

In the full model, there was a significant four-way interaction between lexical precision, NHD, relatedness and prime lexicality (see Figure 4.2.). The full model was split into two sub-models: high lexical precision and low lexical precision. Lexical precision was removed from the equation and the same procedures for the analyses and random structure from the full model were applied to the sub-models. In the high lexical precision sub-model, the interactions between NHD, prime lexicality and relatedness (*b* = 0.01, *t* = 0.39, *p* = .70), prime lexicality and NHD (*b* = -0.004, *t* = -0.20, *p* = 0.85), relatedness and NHD (*b* = -0.014, *t* = -0.66 *p* = 0.51) and prime lexicality and relatedness (*b* =-0.014, *t* = -0.62, *p* = .54) were not significant. In addition, there were no simple effects of relatedness (*b* = -0.010, *t* = 0.62, *p* = .53) and prime lexicality (*b* = -0.007, *t* = 0.43, *p* = .67). However, there was a simple effect of NHD (*b* =- 0.072, *t* = -3.2, *p* = .002). Dyslexic individuals with high lexical precision took longer to reject pseudowords with dense neighbourhood (*M* = 745, SE = 39.0) than pseudowords with sparse neighbourhoods (*M* = 690, SE = 35.6). For dyslexic individuals with low lexical precision, no interaction between NHD, prime lexicality and relatedness was demonstrated, (*b* = -0.009, *t* = -0.31, *p* = .76), no interactions of NHD and prime lexicality (*b* = - 0.011, *t* = 0.56, *p* = .58), of NHD and relatedness (*b* = 0.004, *t* = 0.19, *p* = .85) and prime lexicality and relatedness (*b* = -0.010, *t* = -0.49, *p* = .62) were significantly shown. In addition, there was no simple effect of prime lexicality (*b* = -0.005, *t* = -0.35, *p* = .73). However, there was a simple effect of NHD (*b* = -0.08, *t* = -3.6, *p* < .001) and there was an effect of relatedness that approached significance (*b* = 0.03, *t* = 1.69, *p* = .09). Dyslexic individuals with low lexical precision took longer to reject pseudowords with dense neighbourhood (*M* = 737, SE = 36.5) than pseudowords with sparse neighbourhoods (*M* = 686, SE = 33.6). Dyslexic individuals with low lexical precision showed an overall effect of facilitatory priming.

Pseudoword targets in naming

The same trim as used for word naming was carried out, resulting in 7.5% of the data being removed. Average RTs, SDs, and the proportion of correct responses for each condition are shown in Table 4.10. The priming effects concerning naming latencies were facilitatory for pseudoword targets and the priming effects were smaller for pseudowords with dense neighbourhoods than those with sparse neighbourhoods. The model for pseudoword naming did not converge until the item slope was removed, leaving only a random item intercept. The three-way interaction was reduced to NHD as an individual factor in the random structure for the subject (see appendix E for the final model code for LDT, word naming and pseudoword naming). The output of this model is shown in Table 4.11.

Table 4.10. Mean naming latencies and proportion correct each prime lexicality, relatedness and NHD condition for pseudoword targets in the dyslexic population.

	High N		Low N	
Prime lexicality	Word Prime	Nonword prime	Word Prime	Nonword prime
Related (R)				
RT	535 (139)	537 (137)	531 (139)	543 (144)
P correct	.86 (0.35)	.86 (0.35)	.94 (0.25)	.94 (0.25)
Unrelated (UR)				
RT	550 (128)	547 (135)	555 (147)	555 (145)
P correct	.87 (0.34)	.87 (0.34)	.93 (0.26)	.93 (0.26)
Priming effect				
RT	15	10	26	12
P correct	.01	.01	-.01	-.01

Note. Response times (RT); Proportion (P); Response times are measured in milliseconds and standard deviations are in parentheses.

Table 4.11. The minimal model output for naming pseudoword targets in dyslexic population.

Fixed Effects	Estimate	Std. Error	95% LCI	95% UCI	*t* values
(Intercept)	6.26200	0.02280	6.21731	6.30669	274.66
Priming conditions					
Relatedness	0.01756	0.006048	0.00571	0.02941	2.90*
Prime lexicality	-0.01433	0.006061	-0.02621	-0.00245	-2.36*
Individual Factors					
Lexical precision	-0.05465	0.021770	-0.09732	-0.01198	-2.51*
Interactions					
Prime lexicality * relatedness	0.02157	0.008571	0.00477	0.03837	2.52*

Note. $^{*}p < .05$

The full model produced a significant interaction of prime lexicality and relatedness (Table 4.11). Participants showed smaller facilitatory priming for pseudoword targets preceded by pseudoword primes than those that followed word primes. The full model was split into two sub-models: word and pseudoword primes. Prime lexicality was removed from the equation and the same procedures for the analyses from the full model were applied to the submodel. An effect of relatedness was shown for word targets preceded by word primes (b = 0.04, t = 6.46, p < .001, d = 0.15) and pseudoword primes (b = 0.02, t = 2.97, p = .003, d = 0.07). For pseudoword targets that followed word and pseudoword primes, related primes resulted in shorter naming latencies (M = 533, SE = 3.24; M = 540, SE = 3.27, respectively) than unrelated primes (M = 552, SE = 3.21; M = 551, SE = 3.24).

With regard to the individual factors, the model output showed that there was a significant effect of lexical precision on log RT. Unsurprisingly, the higher the component of lexical precision, the shorter the reaction times.

DISCUSSION

The present study used a suite of individual difference measures to assess whether PWD have an imprecise lexical or sublexical representation that modulates lexical retrieval in visual word recognition and production. An additional aim was to assess whether PWD would perform similarly to people with low phonological precision or low orthographic precision for the LDT and visual word naming respectively. We manipulated NHD, primes and target lexicality in a masked form priming experiment to assess competition resolution in visual word recognition and naming.

The predictions were as follows: based on previous research (see review by Bishop & Snowling, 2004) that PWD have poor orthographic and phonological representations, PWD should perform similarly to people with low phonological and low orthographic precision, showing only facilitatory priming in the LDT. In addition, the interaction of NHD and relatedness would be demonstrated in the visual word naming task such that word targets with dense neighbourhoods show smaller facilitatory priming effects than those with sparse neighbourhoods. According to the LQH, it was predicted that individual differences would contribute to the priming effects such that PWD with high lexical precision should have a more redundant and precise lexical representation, showing inhibitory priming, and those with low lexical precision should demonstrate facilitatory priming. The results of this study partially support both hypotheses. The study supports the LQH, as an overall facilitatory priming effect in PWD was not demonstrated in the LDT, and lexical precision interacted with NHD, prime lexicality and relatedness for word targets. Dyslexic individuals scoring lower on the lexical precision component only showed little, if any, facilitatory priming whereas participants scoring higher on the lexical precision component showed inhibitory priming for word targets with dense neighbourhoods. Dyslexic individuals with high lexical precision showed facilitatory priming for word targets with sparse neighbourhoods that followed pseudoword primes, while inhibitory priming was observed for word targets preceded by word primes. This supports the LQH in that PWD with more precise lexical representations process word primes quickly. In turn, the neighbouring candidates of the prime, which includes the target word, are more easily suppressed. Once the word target appears, lexical competition ensues between the *word* prime and target, resulting in inhibitory priming (Davis & Lupker, 2006). Word targets with sparse neighbourhoods preceded by *pseudoword* primes showed facilitatory priming. It could be argued that PWD may process the pseudoword prime quickly, as this does not need access to the mental lexicon, contradicting the poor grapheme-phoneme correspondence in PWD. However, this may, in fact, be incorrect, as PWD may possess a less stable orthographic representation but struggle to tolerate imprecise letter position coding (Lete & Fayol, 2013). Once the word target appears, the pseudoword prime pre-activates the word at a sublexical level (Davis & Lupker, 2006).

For pseudoword targets, based on Chapter 2, we predicted that only prime lexicality and relatedness would be demonstrated without any individual difference component contributing to the priming effect. The present pattern of results contradicts Chapter 2's findings, as we found that people with high lexical precision showed little, if any, priming effects, while people with low lexical precision demonstrated overall facilitatory priming. This indicates that PWD who have low lexical precision process the pseudoword prime and target at a sublexical level. However, PWD who have high lexical precision are more likely to use the direct and lexical routes and face competition between the prime and target, thus showing little, if any, priming effects. This does not support the findings of Chapter 2, as there were only little, if any, priming effects for pseudoword targets preceded by word primes and facilitatory priming for pseudoword targets following pseudoword primes, which was not moderated by individual differences.

Outcomes were also assessed in word and pseudoword naming. The current study for word and pseudoword naming partially supports the findings in Chapter 3 in that people with low orthographic precision showed an interaction of NHD and relatedness for word naming and prime lexicality and relatedness for pseudoword naming. We predicted that PWD would perform in a similar manner to people with low orthographic precision. In general, results of both word naming and pseudoword naming were contrary to the predictions based on the LQH (see p.69) but aligned with the findings of Chapter 3 for people with low orthographic precision. People with dyslexia showed smaller facilitatory priming for word targets with dense neighbourhoods than those with sparse neighbourhoods. In addition, PWD showed smaller facilitatory priming for pseudoword targets preceded by pseudoword primes than those following word primes. This indicates that an orthographic precision impairment may be one of the causes underlying dyslexia.

Conclusion

The orthographic precision impairment may result from less fluent phonological recoding (Share, 1995). Although it could be argued that this may be due to limited and reduced print exposure (Nation et al., 2018), there was no significant difference between dyslexics and controls in print exposure. This suggests that vocabulary and print exposure contribute to the development of a precise orthographic representation, but this is not sufficient in PWD. One plausible explanation is that vocabulary and print exposure may lead to the development of a robust and precise lexical representation, but phonological recoding needs to be fluent to contribute to the development of a phonological representation. Perry, Zorzi and Ziegler (2019) used a developmental computational model of reading acquisition to assess how the core deficits of dyslexia determined individual learning outcomes for 388 children with dyslexia and 234 control children. They found that the learning trajectories could be simulated based on three component abilities linked to orthography, phonology and vocabulary. The single-deficit models (i.e. phonological, semantics or orthography) did not capture the distribution of reading scores, but multiple-deficit models (phonology, orthography and semantics) captured most of the distribution of reading ability.

Interestingly, the PCA for people with dyslexia shown in the current study supports the multiple-deficit model, as orthography, phonology and semantics were included as one component, which was indicative of lexical precision. This suggests that the causes of dyslexia are likely to be at the low-level processes of word recognition and that phonological decoding and orthographic precision impairments may contribute to the pathogenesis of dyslexia.

CHAPTER 5.

DO DYSLEXIA AND STUTTERING SHARE A PROCESSING DEFICIT?[19]

[19] This chapter is currently under review: Elsherif, Wheeldon, L.R., & Frisson, S. Do dyslexia and stuttering share a processing deficit?

ABSTRACT

This study assessed the prevalence of childhood stuttering in people with dyslexia (PWD) and the prevalence of dyslexia in people who stutter (PWS). In addition, the linguistic profiles of 50 PWD, 30 PWS and 84 neurotypical adults were measured. We found that 17 out of 50 PWD (34%) reported stuttering during childhood compared to 1% of the controls. This was moderated by the severity of dyslexia: People with mild dyslexia showed a lower prevalence rate (15%) of childhood stuttering than those with severe dyslexia (47%). In addition, we observed that 50% of the PWS (n = 30) fulfilled the diagnostic criteria of dyslexia, even though they had never been diagnosed as dyslexic. Finally, PWD and PWS did not differ on any phonological measure. The findings suggest that stuttering and dyslexia may share a common phonological deficit.

Keywords: Dyslexia; stuttering; phonological processing; orthographic processing; semantics

INTRODUCTION

Dyslexia is a common neurodevelopmental condition, which manifests itself in the form of reading difficulties and occurs in 7-10% of the population (Peterson & Pennington, 2012). Neuroimaging studies have shown structural and functional neural differences in dyslexics compared to neurotypical controls (Richlan, 2012; Richlan, Kronbichler & Wimmer, 2009, 2011, 2013). People with dyslexia (PWD) show a dysfunction in the left hemisphere reading network, which includes the occipito-temporal, inferior frontal gyrus and inferior parietal regions (Richlan, 2012; Richlan et al., 2009, 2011, 2013). These regions are involved with phonological decoding and access to the phonological output lexicon and attentional mechanisms, respectively (Richlan, 2012; Richlan et al., 2009, 2011, 2013). According to the phonological deficit hypothesis (Snowling, 2000), individuals with dyslexia have deficient phonological representations and struggle to connect sounds to letters. This impairment leads to a poor build-up of the orthographic lexicon, resulting in difficulties with reading (Bradley & Bryant, 1983; Share, 1995).

Stuttering is a neurodevelopmental disorder that results in difficulties with formulating motor plans for speech production and occurs in 1% of the adult population and in 5% of children (Guitar, 2013). The stuttering brain is anatomically and functionally different from the typical brain (Chang, Erickson, Ambrose, Hasegawa-Johnson & Ludlow, 2008; Watkins, Smith, Davis & Howell, 2007). Differences are found in the left Brodmann Area 47/12, left Heschl's gyrus, left motor cortex, left inferior frontal gyrus and bilateral temporal regions, which are related to syntactic and semantic processing, auditory processing, language production and comprehension, and manipulation of articulators, respectively (Chang et al., 2008; Watkins et al., 2007). These differences are primarily found in the left hemisphere and in areas associated with phonological processing in the neurotypical population (Lavidor & Ellis, 2003). Both PWD and people who stutter (PWS) therefore show impairments in the left inferior frontal gyrus. Here we test the possibility that both disorders share an underlying deficit in phonological processing.

If dyslexia and stuttering are independent, then only 5% of PWD (and less than 1% of the general population) should have stuttered as a child. However, evidence suggests that these conditions may not be as independent as commonly assumed. For example, both stuttering and dyslexia have been shown to share similar genetic alleles (e.g. DRD2, GNPTAB and NAGPTA; Chen et al., 2014, 2015) and are related to speech production deficits (Malek, Amiri, Hekmati, Pirzadeh & Gholizadeh, 2013; see review by Snowling & Melby-Lervag, 2016 for speech production deficits in PWD).

The notion that stuttering and other types of speech difficulties may be more common in dyslexia has been raised before, but the evidence is largely anecdotal and does not distinguish between the different kinds of speech difficulties (Blood, Ridenour Jr, Qualls & Hammer, 2003;

Chen et al., 2014, 2015; Malek et al., 2013; Rabkin, 1956; Snowling & Melby-Lervag, 2016). Orton (1928) suggested that PWD tend to stutter due to a confusion of cerebral dominance, however, data to support this claim is limited. Childhood stuttering is known to be associated with a wide range of language deficits such as difficulties in nonword repetition and phoneme-related tasks (Anderson, Wagovich & Hall, 2006; Pelczarski & Yaruss, 2014). The vast majority of children who stutter during childhood recover from stuttering without intervention prior to the age of 16 (Andrews et al., 1983). However, it has been suggested that recovery from childhood stuttering may still show long-term effects. For example, Chang et al. (2008) found that relative to a control group, adolescents who recovered from stuttering and those with persistent stuttering had a reduced grey matter volume in the left inferior frontal gyrus and bilateral temporal regions, possibly related to speech production.

The present study measured the rate of childhood stuttering in PWD compared to a control group to determine if the rate of co-occurrence is greater than would be predicted if the conditions were independent. In addition, we compared PWD to PWS and neurotypical controls in order to establish to what degree their phonological processing profiles matched. While a determining factor in PWD is a significant phonological deficit, it is at present not known whether PWS present a similar deficit. Based on previous research, we predict that as PWD have spelling and reading comprehension difficulties (see review by Bishop & Snowling, 2004; Ransby & Swanson, 2003), while PWS do not, PWS should perform better than PWD on measures of spelling and reading comprehension. However, if both groups share a phonological impairment, they should not differ with regard to phonological skills.

METHOD

Participants

Originally, 92 monolingual British undergraduate students without language impairment aged 18-22 (M=20.1±1.1 years) from the University of Birmingham participated in the study in return for course credits or remuneration. Six participants were excluded due to attrition and two due to the exclusion criteria to define dyslexia (see below). Fifty PWD aged 18-32 (M=20.7±2.7 years; 27 males), recruited from local universities, and 30 PWS aged 18-48 years (M=29.5±8.91 years; 22 males) participated for remuneration. Participants were matched as closely as possible in terms of age, educational level, bilingualism and handedness (see Table 5.1.). It should be noted that 30 PWS is a rather large sample size in the stuttering literature as PWS are notoriously challenging to recruit, likely due to the perceived negative stereotyping associated with the condition. Mirroring prevalence rates in the general population, there were more male participants in both the dyslexia and stuttering groups. All adult participants with dyslexia provided a diagnostic report documenting a childhood history of dyslexia and had no history of attention deficit hyperactivity disorder or a current diagnosis of persistent stuttering using the DSM-V criteria. In addition, none of the PWS had a history of attention deficit hyperactivity disorder or a current diagnosis of dyslexia using DSM-V criteria. The study was conducted in accordance with the British Psychological Society ethical guidelines and approved by the University's ethical committee. All participants had normal or corrected-to-normal vision and signed a consent form.

Education level was classified as A-levels (coded as 1), Bachelors (coded as 2), Masters (coded as 3) and PhD (coded as 4). The homogeneity of variance between groups was assessed with the Fligner Killeen test. The dyslexia and control groups did not differ significantly from each other in terms of average education level ($t(77.27)=-1.86$, $p=.07$), bilingualism ($t(132)=-1.86$, $p=.07$), or age ($t(57.80)=-1.36$, $p=.18$), but there were significantly more males ($t(67.10)=-5.90$, $p<.001$) and left-handed individuals ($t(89.37)=-3.30$, $p=.001$) in the dyslexia than in the control group. The stuttering and control groups did not differ significantly from each other in terms of average education level ($t(112)=-1.51$, $p=.13$), bilingualism ($t(29)=-1.44$, $p=.16$) or handedness ($t(112)=-0.32$, $p=.76$), but there were significantly more males ($t(37.21)=-7.43$, $p<.001$) and older individuals ($t(29.28)=-5.60$, $p<.001$) in the stuttering group than in the control group. The stuttering and dyslexia groups did not differ significantly from each other in terms of gender ($t(80)=-1.73$, $p=.09$), bilingualism ($t(78)=-0.52$, $p=.60$), or average education level ($t(78)=0.08$, $p=.94$) but the average age was higher in the stuttering than in the dyslexia group ($t(32.13)=-5.15$, $p<.001$), and there were more left-handed individuals in the people with dyslexia (PWD) than the people who stutter (PWS) group ($t(75.85)=2.63$, $p=.01$).

Table 5.1. The means and standard deviation for demographic variables for all diagnostic groups.

	Controls (*N* = 84)	**Dyslexics (*N* = 50)**	**Stuttering (*N* = 30)**
	Mean (*SD*)	**Mean (*SD*)**	**Mean (*SD*)**
Age (year)	20.18 (1.03)	20.72 (2.7)	29.47 (8.91)
Education	1.04 (0.23)	1.14 (0.35)	1.13 (0.43)
Gender (%female)	91.7 (0.28)	46 (0.50)	27 (0.42)
Handedness (%Right)	89 (0.41)	62 (0.49)	87 (0.33)
Bilingualism (%Bilingual)	0 (0)	4 (0.20)	7 (0.25)

Standardized tests

Demographic questionnaire. This questionnaire collected background information on participants, including age, gender and handedness.

Language measures.

Print exposure. Print exposure included the Author Recognition Test (ART) adapted from (Stanovich & West, 1989) and the Title Recognition Test (TRT) adapted from (Cunningham & Stanovich, 1990). The ART is a checklist which requires participants to choose whether they are familiar with the name of an author by ticking their name. The ART checklist consists of 100 names (50 real author names and 50 foils). The TRT followed the same procedures as the ART, with participants ticking familiar book titles including plays, poetry and novels (TRT). The TRT checklist had 100 book titles (50 real and 50 foils). We modified the original tests to include current and classic authors, together with book titles from Amazon's top 100 authors, for a British audience. (A pre-test with 100 additional participants from the same population showed a normal distribution in their answers). There was no time limit for completing the checklists. For each participant, a score was calculated by subtracting the number of ticked foils (i.e. false alarms) ticked from the number of correctly recognized authors (i.e. hits).

Receptive vocabulary. The British Picture Vocabulary Scale 2nd edition (BPVS-II; Dunn, Dunn, Whetton & Burley, 1997) was used to measure the participants' receptive vocabulary. The participant orally presented with a word and was asked to select the corresponding picture from a choice of four. Each participant completed six vocabulary sets (Sets 9-14). E-prime (E-studio, E-prime 2.0) software was used to implement this task. The correct answers were recorded and totalled for each participant.

Reading Fluency. The sight word efficiency and non-word reading (phonemic decoding) subtests from the Test of Word Reading Efficiency (TOWRE; Torgesen, Rashotte & Wagner, 1999) and the Test of Irregular Word Reading Efficiency (TIWRE; Reynolds & Kamphaus, 2007) were used to assess reading fluency. In addition, the Stuttering Severity Instrument, version 3 (SSI-3: Riley, 1994) was used as a standardised measure to determine stuttering severity. The TOWRE sight word reading required the participant to read out loud as many printed words out of 108 or the or pronounceable pseudowords out of 66 as possible within 45 seconds (TOWRE phonemic decoding). The third test (TIWRE): required participants to read 25 irregular words with no time limit. The number of correct answers in each test was recorded for each participant. Finally, SSI-3 required each PWS provided a conversational speech sample and read a text passage aloud. We videotaped speech samples. The frequency of stuttering events in conversational speech and reading samples, and the duration of stuttering events and the frequency of behaviours peripheral to stuttering (i.e. physical concomitants) are combined in the SSI-3, providing a single score to indicate the severity of stuttering. The average score on SSI-3 across PWS was 21.9, which is classified as mild (range: 10-37; mild to severe stuttering severity).To ensure our tests assessed articulatory processes, we correlated the relationship between stuttering severity and TOWRE phonemic and word reading efficiency, along with TIWRE and RLN (r=-0.15; p=.43, for TIWRE, r=.66; p<.001 for TOWRE phonemic decoding, r=.79; p<.001 for TOWRE word reading and r=.45; p<.001 for the RLN test). This indicates that the TOWRE phonemic decoding, TOWRE word reading and RLN measure articulatory mechanisms, with more severe stutterers performing worse on these tests, while TIWRE may not be an adequate measure of articulation.

Phonological processing. The following subtests from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen & Rashotte, 1999): phoneme elision, Rapid Letter naming (RLN), memory for digits, non-word repetition and phoneme reversal to measure phonological processing. In the phoneme elision task, the participant had to remove a given phoneme from a word and to say the resulting word (e.g. *mat* without /m/ is *at*). In the non-word repetition task, the participant heard pseudowords and had to repeat them back to the experimenter. In the phoneme reversal task, the participant heard a phoneme or pseudoword and had to reverse the phoneme or pseudoword to form a real word (e.g. *na* forms *an*). In all three tasks there were 18 items and the number of correct answers was recorded. In the RLN, the participant had to name 36 printed letters as quickly as possible, and the time taken to name all letters was recorded. In the memory for digits test, the participant heard digits and had to repeat them back to the experimenter. There were 21 items and the number of correct answers was recorded.

Reading comprehension. In the Gray Silent Reading Test (GSRT; Wiederholt & Blalock, 2000), each participant read six brief stories (Stories 4-9) silently. The stories increased in complexity. The participant had to answer five multiple choice questions per story with no time limit. E-prime software was used to implement this task. The number of correct answers was recorded.

Expressive vocabulary. In the Expressive Vocabulary Test second edition (EVT-2; Williams, 2007), the participant was asked to name objects (e.g. *astronaut*) or to describe what a person was doing (e.g. *singing*) with reference to a picture. There were 109 items and the number of correct answers was recorded.

Spelling. The spelling subtest was based on the British Ability Scale (Elliott, Smith & McCulloch, 1996). Twenty words were dictated to the participant, which they had to spell accurately. The number of correctly spelled words was recorded.

Manual Stroop task. This task required participants to indicate whether a font colour and a word (font: Arial, size: 34) were the same or not. For instance, if participants saw the word BLUE with the font colour blue (congruent), they had to press 'YES' with their dominant hand to indicate they were the same. If the font colour was red instead of blue (incongruent), they had to press the 'NO' button with their non-dominant hand to indicate they were different. This test allowed us to investigate the role of inhibitory control during word recognition. Each trial began with a fixation cross of 500ms followed by the target, to which they had to respond within 2000ms. The present study used 25 incongruent trials and 75 congruent trials, forcing participants to maintain the goal of word naming rather than focusing primarily on the goal of colour naming (e.g. Stroop, 1935). E-prime (E-studio, E-prime 2.0) software was used to implement this task. Responses were recorded via a keyboard. For each participant, the average reaction time for the correct answers and the proportion correct were recorded**.** An inverse efficiency score (IES) was calculated (Bruyer

& Brysbaert, 2011; Townsend & Ashby, 1978), which is an aggregated measure that combines speed and accuracy in one measure.

The equation is below:

$$IES = \frac{RT}{PC}$$

IES is calculated by dividing reaction time (RT) by the proportion of correct responses (PC); smaller numbers indicate greater efficiency (Bruyer & Brysbaert, 2011; Townsend & Ashby, 1978).

Naming Stroop task. Participants saw a coloured word and had to name the font colour, not the word (font: Arial, size: 43; Stroop, 1935). For instance, participants saw the word BLUE with the font colour blue (congruent) and had to say BLUE. If the font colour was red instead of blue (incongruent), they had to say RED. The same procedure and scoring system were used as for the Manual Stroop task. Responses were recorded with a voice key.

Non-verbal intelligence measure. The Raven's Standard Matrices test assessed non-verbal intelligence (Raven, 1960). Participants were shown 60 patterns of increasing complexity and had to select which pieces completed each complex pattern. E-prime (E-studio, E-prime 2.0) software was used to implement this task. The number of correct answers was recorded.

Procedure

At the beginning of the study, participants were given a demographic questionnaire, which collected background information including age, gender, handedness, bilingual, education level, type of intervention (e.g. speech-language therapy), history of dyslexia and history of stuttering, inter alia. A clear definition of stuttering (based on the definition provided by Guitar, 2013) was provided on the participant information sheet. If participants stated on the questionnaire that they had stuttered as a child, they were asked to verify this verbally and with evidence from their educational reports. After filling out the questionnaire, participants completed a battery of tasks designed to test phonology, vocabulary, reading comprehension, inhibitory control and reading fluency.

Data analyses.

All analyses were two-sided and the α value used to indicate significance was .05. All data were analysed within the R statistical programming environment, version 1.1.456 (R Core Team, 2015) The package 'tidyverse' version 1.1.1 (Wickham, 2017) was used for data processing. The package 'lsr' 0.5.0 (Navarro, 2015) was used to compute Cramer's *V*. The package 'effsize' 0.7.4 (Torchiano, 2017) was used to compute Cohen's *d*. The package 'DescTools' 0.99.30 (Signorell, 2019) was used to compute *G* tests of independence. The data, scripts and materials for all experiments are available at the open science framework at https://osf.io/wzd6k/. None of the experiments were pre-registered. Prior to making any comparisons and to better understand the differences between PWS and PWD, we analysed the responses between groups for each standardised test with an independent *t*-test. In order to reduce the chance of finding a type I error, we used a Bonferroni correction to report the significance of tests that were not planned (corrected α value: 0.05/8=0.00625). Hence, all the tests excluding those that assessed phonological processing and reading fluency measures have the corrected *p*-value.

Post-hoc power analyses. As there currently is no good evidence we could rely on to calculate expected effect sizes, we performed post-hoc power analyses on the G test for the prevalence rates and independent *t*-test for group differences in terms of the composite scores (see below for calculations) using G*Power (Faul, & Erdfelder, Buchner & Lang, 2009). The degrees of freedom, total sample size and effect size were set according to test-specific calculations in R. The power analyses described below indicate that the analyses within the PWS and PWD groups might be underpowered to confidently assess small effects. However, our main findings have medium-to-large effect sizes (.5 to .8), and, thus, do not suffer from a lack of power. In addition, a post-hoc power that was above 0.99 (hereon abbreviated as: post-hoc power > 0.99) indicates that the effect size is large and replicable.

RESULTS

Prevalence of childhood stuttering in people with dyslexia and control.

Our findings showed that among the 50 PWD, 17 (6 female) stuttered as a child (a rate of childhood stuttering of 34%; 95%CI[20.7, 47.3]), which was significantly higher than the 1% (n=1; 1 male; 95%CI[-1.14, 3.52]) who stuttered as a child among the 84 controls ($G(1, N=134)=30.78$, $p<.001$, $V=.44$, post-hoc power > 0.99). In addition, we divided our PWD into subcategories of mild and severe dyslexia based on 2SD below the mean of the control population in measures of phonological processing and reading fluency to assess whether the severity of dyslexia affected the prevalence of childhood stuttering. We observed that among the 20 people with mild dyslexia, 3 (1 female) stuttered as a child (a childhood stuttering rate of 15%), which was significantly higher than the 1% who stuttered as a child among the 84 controls ($G(1, N=104)=6.15$, $p=.01$, $V=.22$, post-hoc power = 0.61). Finally, we observed that among the 30 people with severe dyslexia, 14 (5 female) stuttered as a child (a childhood stuttering rate of 47%), which was significantly higher than the 1% who stuttered as a child among the 84 controls ($G(1, N=114)=36.47$, $p<.001$, $V=.56$, post-hoc power > 0.99). In addition, we compared people with severe dyslexia and people with mild dyslexia to assess whether childhood stuttering is more prevalent in the former than the latter. The relation between these variables was significant, ($G(1, N=50)=5.74$, $p=.02$, V=.28, post-hoc power = 0.51): more people with severe dyslexia had stuttered during childhood than those with mild dyslexia.

Prevalence of dyslexia in people who stutter.

When applying the diagnosis of dyslexia to PWS (i.e.2SD below the mean of the control population in measures of CTOPP that assesses phonological processing, spelling and measures of TOWRE sight word efficiency, phonemic decoding and TIWRE that evaluates reading fluency; Hanley, 1997), we found that 50% of the 30 PWS (*n*=15; 3 males; 95%CI[31.8,68.2]) matched the diagnostic criteria for dyslexia, which was significantly higher than the 2% among the controls (*n*=2; 0 females; 95%CI[-0.889, 5.59]) ($G(1, N=116)=36.08$, $p<.001$, $V=.56$ post-hoc power > 0.99). It should be emphasized that none of the PWS had received a prior clinical diagnosis of dyslexia.

Differences between populations on standardised tests

Planned comparisons. Average results of each standardised test for each population are shown in Table 5.2. The inferential data with *t* values, *p* values, effect size and 95% confidence intervals are shown in Table 5.3. Planned contrasts revealed that PWD and PWS performed worse than the control population on the phonological processing and reading fluency measures. In addition, PWD performed worse than the controls on phoneme reversal, but there was no difference between PWS and controls on this task. PWD and PWS did not differ on the following measures: TOWRE word reading and TOWRE phonemic decoding, CTOPP phoneme elision, memory for digits, nonword repetition, RLN and phoneme reversal.

Post-hoc analyses. PWD performed worse than the controls on the spelling measure, with PWS not significantly different from either group. There was no difference among the three groups in the manual Stroop task, naming Stroop task, Raven, GSRT, TIWRE, BPVS-2 and EVT-2. In addition, PWD did not differ from PWS in print exposure. The PWS showed a significantly higher print exposure than the neurotypical population.

Table 5.2. Behavioural profile of the control, dyslexic and stuttering population.

	Controls (*N* = 84)	**Dyslexics (*N* = 50)**	**Stuttering (*N* = 30)**
	Mean (*SD*)	**Mean (*SD*)**	**Mean (*SD*)**
Raven (/60)	45.48 (6.57)	47.38 (7.13)	43.93 (10.48)
GSRT (/30)	22.25 (3.33)	21.18 (4.05)	23.27 (4.53)
Print Exposure (/100)	34.06 (13.07)	35.42 (17.81)	50.03 (25.51)
BPVS-2	42.74(7.27)	42.40 (7.78)	39.60 (9.93)
EVT-2	71.86 (8.01)	72.95 (10.36)	77.80 (13.93)
TOWRE-W (/ 108)	87.34 (11.24)	78.82 (12.10)	73.73 (20.10)
TOWRE-P (/60)	57.88 (5.56)	49.3 (7.15)	51.87 (10.94)
TIWRE (/ 25)	21.19 (1.86)	20.26 (2.25)	21.57 (2.88)
Spelling (/20)	16.49 (2.37)	13.24 (2.95)	14.87 (4.19)
Manual Stroop (IES)	134 (97)	157.79 (75.60)	144.34 (103.35)
Naming Stroop (IES)	190 (137)	213.02 (104.81)	205.95 (125.36)
Phoneme elision (/20)	16.67 (2.38)	15.32 (3.04)	15.07 (3.60)
Memory for digits (/21)	16.65 (2.14)	14.34 (2.04)	15.33 (3.08)
Nonword repetition(/18)	13.68 (1.73)	10.68 (2.23)	9.9 (2.90)
RLN (ms)	26.27 (4.79)	32.59 (9.42)	42.13 (52.94)
Phoneme reversal (/18)	11.43 (2.62)	8.96 (2.49)	9.93 (3.83)

Note. Total print exposure assessed by author and title recognition**;** inverse efficiency scores (IES); British Picture Vocabulary Scales 2nd edition (BPVS-2); Expressive Picture Vocabulary Test 2nd edition (EVT-2); Gray Silent Reading Test (GSRT); Rapid Letter naming (RLN); Test of Word Reading Efficiency (TOWRE): sight word reading (TOWRE-W) and phonemic decoding (TOWRE-P) and Test of Irregular Word Efficiency (TIWRE).

Table 5.3. Model comparison between populations and standardised tests

	Controls vs Dyslexia	**Controls vs Stuttering**	**Dyslexia vs. Stuttering**
Raven	*t*(132) = -1.57, *p* = .12, *d* = -0.27	*t*(37.15 [a]) = 0.74, *p* = .46, *d* = 0.20	*t*(45.05 [a]) = 1.57, *p* = .12, *d* = 0.40
GSRT	*t*(132) = 1.64, *p* = .10, *d* = 0.29	*t*(112) = -1.29, *p* = .20, *d* = -0.27	*t*(78) = -2.11, *p* = .04, *d* = -0.49
Total print exposure	*t*(132) = -0.47, *p* = .64, *d* = -0.09	**_t_(34.46 [a]) = -3.23, _p_ = .003, _d_ = -0.91**	*t*(45.88 [a]) = -2.71, *p* = .009, *d* = -0.69
BPVS-2	*t*(132) = 0.25, *p* = .80, *d* = 0.04	*t*(112) = -1.82, *p* = .07, *d* = 0.39	*t*(78) = 1.38, *p* = .17, *d* = 0.31
EVT-2	*t*(132) = -0.69, *p* = .49, *d* = -0.12	*t*(35.91 [a]) = -2.17, *p* = .04, *d* = -0.59	*t*(48.03 [a]) = -1.61, *p* = .11, *d* = -0.40
TOWRE-W	**_t_(132) = 4.10, _p_ < .001, _d_ = 0.73**	**_t_(35.28 [a]) = 3.46, _p_ = .0014, _d_ = 0.96**	*t*(41.63 [a]) = 1.24, *p* = .22, *d* = 0.32
TOWRE-P	**_t_(132) = 7.69, _p_ < .001, _d_ = 1.37**	**_t_(34.38 [a]) = 2.83, _p_ = .007, _d_ = 0.81**	*t*(43.86 [a]) = -1.13, *p* = .27, *d* = -0.29
TIWRE	*t*(132) = 2.56, *p* = .01, *d* = 0.46	*t*(37.78 [a]) = -0.66, *p* = .52, *d* = -0.17	*t*(78) = -2.23, *p* = .03, *d* = -0.51
Spelling	**_t_(132) = 6.93, _p_ < .001, _d_ = 1.24**	*t*(35.70 [a]) = 1.97, *p* = .06, *d* = 0.54	*t*(46.14 [a]) = -1.84, *p* = .07, *d* = -0.46
Manual Stroop	*t*(132) = -1.47, *p* = .14, *d* = -0.26	*t*(112) =-0.48, *p* = .63, *d* = -0.10	*t*(78) = 0.66, *p* = .51, *d* = 0.15
Naming Stroop	*t*(132) = -1.02, *p* = .31, *d* = -0.18	*t*(112) = -0.56, *p* = .58, *d* = -0.12	*t*(78) = 0.27, *p* = .79, *d* = 0.06
Phoneme elision	**_t_(84.36 [a]) = 2.66, _p_ = .009, _d_ = 0.51**	**_t_(38.22 [a]) = 2.23, _p_ = .03, _d_ = 0.58**	*t*(78) = 0.33, *p* = .74, *d* = 0.08
Memory for digits	**_t_(132) = 6.12, _p_ < .001, _d_ = 1.09**	**_t_(39.22 [a]) = 2.14, _p_ = .04, _d_ = 0.54**	*t*(44.18 [a]) = -1.55, *p* = .13, *d* = -0.40
Nonword repetition	**_t_(132) = 8.63, _p_ < .001, _d_ = 1.54**	**_t_(36.42 [a]) = 6.61, _p_ < .001, _d_ = 1.78**	*t*(78) = 1.33, *p* = .19, *d* = 0.31
RLN	**_t_(132) = -5.10, p < .001, _d_ = -0.91**	**_t_(112) = -2.69, _p_ = .008, _d_ = -0.57**	*t*(78) = -1.23, *p* = .22, *d* = -0.28
Phoneme reversal	**_t_(132) = 5.37, _p_ < .001, _d_ = 0.96**	*t*(38.94 [a]) = 1.95, *p* = .06, *d* = 0.50	*t*(43.75 [a]) = -1.25, *p* = .22, *d* = -0.32

Note. Total print exposure assessed by author and title recognition, inverse efficiency scores (IES), British Picture Vocabulary Scales 2nd edition (BPVS-2), Expressive Picture Vocabulary Test 2nd edition (EVT-2), Rapid Letter Naming (RLN), Gray Silent Reading Test (GSRT); Test of Word Reading Efficiency (TOWRE): sight word reading (TOWRE-W) and phonemic decoding (TOWRE-P) and Test of Irregular Word Efficiency (TIWRE). a= The degrees of freedoms were re-calculated as the homogeneity of variance was unequal (Fligner-Killeen test of homogeneity of variance, n.d). Significant effects after Bonferroni correction are in bold.

In a second batch of analyses we calculated composite scores for key measures (Silverstein, 1981). A composite measure of vocabulary (ZVocab) was formed by averaging the raw scores of two strongly correlated vocabulary measures (i.e. EVT-2 and BPVS-2; r=.61) to provide a more comprehensive measure of vocabulary ability. To form a composite measure of phonological working memory (ZMemory), the raw scores of the two highly correlated measures of phonological working memory (i.e. nonword repetition and memory for digits; r=.53) were combined. In addition, we included the raw scores of two highly correlated measures of reading fluency (TOWRE word reading and phonemic decoding; r=.67) as one averaged measure as an assessment of reading fluency (ZReadingFluency). We found that PWD performed worse than the neurotypical population on ZMemory (t(132)=8.81, p<.001, d=1.57, post-hoc power > .99) and ZReadingFluency (t(132)=5.97, p<.001, d=1.07, post-hoc power > .99), but not ZVocab (t(132)=-0.30, p=.77, d=-0.05, post-hoc power = 0.06). Similarly, PWS performed worse than the neurotypical population on ZMemory (t(37.134)=4.90, p<.001, d=1.30, post-hoc power > .99) and ZReadingFluency (t(34.61)=3.48, p=.001, d=0.99, post-hoc power > .99), but not ZVocab (t(36.22)=-0.61, p=.54, d=-0.17, post-hoc power = 0.06). There were no differences between PWD and PWS for ZVocab (t(45.40)=-0.41, p=.68, d=-0.17, post-hoc power = 0.11), ZMemory (t(44.18)=-0.19, p=.85, d=-0.05, post-hoc power = 0.06) or ZReadingFluency (t(78)=.48, p=.63, d=0.11, post-hoc power = 0.08)[20].

DISCUSSION

Childhood stuttering is significantly higher in PWD (34%) than in neurotypical adults (1%), while, if stuttering and dyslexia were independent, a co-occurrence rate of about 5% would have been expected. This was found to be moderated by the severity of dyslexia. The more severe the dyslexia,

[20] Although our groups were not matched on gender, we compared females between groups as there were more females in the control population. Despite the small sample size, female controls performed better than females PWD and PWS in all phonological processing measures, excluding phoneme elision. Phoneme elision did not differ between female controls and PWD or PWS. Female PWD and PWS performed similarly on tests of phonological processing and reading fluency. This highlights that the phonological difficulty is shared between both conditions, irrespective of gender.

the higher the probability of childhood stuttering. While our control group showed a somewhat lower than expected stuttering-as-a-child rate (1%) than the expected 5%, this might be due to a lower percentage of PWS entering higher education, people with severe stuttering tend to have a lower education attainment than those with mild stuttering, possibly due to severe teasing and social ostracism (O'Brian, Jones, Packman, Menzies & Onslow, 2011). If this is the case, the values for childhood stuttering that have been shown in the present study for both the PWD and the control group may be underestimated. In addition, we found that the dyslexia profile was significantly higher in PWS (50%) than in neurotypical adults (2%). Overall, the present findings provide strong evidence for inter-dependency between dyslexia and stuttering that does not result from a statistical artefact or how the conditions are defined (Bishop & Snowling, 2004). It is important to mention that we showed a higher rate of co-occurrence for dyslexia and stuttering in a college sample of high-functioning dyslexics, and our results would need to be assessed in the general population to ensure that they are generalizable to the wider population (Simons, Shoda & Lindsay, 2017).

The dyslexia and stuttering groups performed equally well on the higher-level reading measures for reading comprehension and print exposure, and did not differ on the phonological, vocabulary and reading fluency tasks (involving word reading, phonemic decoding-pseudoword reading and reading irregular words; see Tables 5.2. and 5.3.). Hence, while both groups performed worse than controls on these measures, PWD and PWS had similar levels of phonological processing and access to phonological form. It is important to note that phonological processing tasks require a variety of different skills, and pre-existing knowledge (Bishop & Snowling, 2004). Our findings are consistent with an underlying phonological impairment in both groups that we tested. However, further research is required to determine the exact nature of the phonological deficit.

One limitation of the current study could be that the control group contained children who recovered from stuttering. Unlike PWD, who provided a certified educational report indicating that they had stuttered, controls did not have an educational report providing the same level of detail. This may underestimate the prevalence rate for the control population. Future studies, with a longitudinal design, would provide a clearer picture of how stuttering affects language processing in neurotypical and dyslexic populations and reduce the retrospective nature of reporting by adults. Nevertheless, even the expected 5% childhood stuttering prevalence typically found in a control population falls far short of the 34% found in our PWD sample.

An important clinical implication is that the early speech and language development of both PWS and PWD should be carefully monitored, as these individuals are at increased risk of speech, language and literacy impairments. In addition, screening on a measure of phonological processing, such as nonword repetition, and a measure of broader articulatory skills, such as TOWRE, would allow practitioners to identify individuals at risk of different literacy and speech difficulties and provide appropriate support for PWS and PWD. Finally, we maintain that the childhood stuttering profile in PWD, together with the dyslexia profile in PWS, should be considered in all future studies assessing language-based processes in these groups.

In conclusion, we have shown that the rate of childhood stuttering in PWD is much higher than expected (34 times higher in our sample) and that 50% of our PWS fulfilled the diagnostic criteria of dyslexia (5 to 7 times higher than in the general population). In addition, PWD and PWS showed similarly poor performance on measures of phonological and articulatory processing compared to controls. Together these results suggest that dyslexia and stuttering might be more similar than previously assumed and may share a phonological deficit.

CHAPTER 6.

GENERAL DISCUSSION

The controversy surrounding the individual differences underlying word recognition and production emanates from mixed findings showing the complex relationship between reading and its subcomponents, thus making it difficult to come to a consensus on how the subcomponents affect visual word recognition and production (see review by Andrews, 2012, 2015; Davis & Lupker, 2006). For instance, if one subcomponent of literacy such as orthography improves, this does not necessarily mean that reading is also improved (e.g. Melby-Lervag et al., 2012), but others (e.g. Nation, 2017) argue that orthography, in the form of print exposure, plays an important role in reading development. In addition, if the claim that reading is driven by orthography is correct, this calls into question whether interventions that focus on phonology to ameliorate the manifestations of dyslexia should (also) focus on orthography. This thesis aimed to contribute to our understanding of silent reading and reading aloud by using a masked form priming paradigm in combination with a suite of individual difference measures that assesses orthography, phonology and semantics in the neurotypical population and PWD, a group with poor phonological and orthographic representations (Bishop & Snowling, 2004).

Competition resolution for reading in the neurotypical population

When reading, an individual needs to activate the mental representation of a visually encountered word to retrieve its meaning. This lexical retrieval process requires readers to select the correct lexical representation from a set of possible candidates or neighbours. Activated lexical representations inhibit their neighbours, allowing the best matching candidate to suppress words with similar forms (i.e. competition resolution). According to the LQH (Perfetti, 2007), the components that contribute to competition resolution are: lexical precision, redundancy and semantic coherence. People with precise and redundant lexical representations can suppress competitors in order to recognise a word more easily than those with less precise and redundant lexical representations. A masked form priming paradigm was used to assess competition resolution during visual word recognition and production in a lexical decision task (LDT; Chapter 2) and in word naming (Chapter 3). These two different tasks were used to assess the different stages of lexical retrieval, as it has been found that word naming correlates with the earlier stages of lexical retrieval, whereas the LDT relates to the later stages of lexical retrieval (Schilling et al., 1998). It could be seen that visual word naming is affected more by sublexical processes than the LDT which is strongly influenced by lexical processes (see review by Rastle & Brysbaert, 2006).As a result, facilitatory form priming is consistently shown in visual word naming, while facilitatory and inhibitory priming is more likely to ensue in the LDT (Rastle & Brysbaert, 2006). Using these two methodologies, we assessed the different stages of lexical retrieval, providing converging evidence to either support or contradict the LQH. We manipulated prime lexicality, together with target lexicality such that participants had to discriminate between words and pseudowords or read either words or pseudowords, allowing us to evaluate the role of redundancy with and without lexical precision and semantic coherence. Related word primes strongly activate the target's lexical competitors, increasing the effects of lexical competition. Related pseudoword primes should not engender lexical competition because nonwords are not lexically represented, resulting in facilitatory priming with the prime pre-activating the processing of the target. Hence, word targets allow us to focus on semantic coherence, lexical precision and redundancy, while pseudowords allow us to focus on the redundancy factor in isolation.

The prediction for the neurotypical population was that more skilled readers would show inhibitory priming and reduced facilitatory priming in word targets for LDT and word naming respectively, as more skilled readers should be able to quickly suppress the neighbouring candidates, including the target. Once the target appears, it will therefore take longer to recognise and produce the word compared to the situation where the target word had not been suppressed (non-overlapping prime). To assess competition resolution, we manipulated neighbourhood density (NHD), as lexical competition is more likely to occur for words with a higher number of neighbours, as the lexical space becomes denser and more finely tuned (Forster & Taft, 1994). More skilled readers would show inhibitory priming, indicative of lexical competition, for word targets with dense neighbourhoods, while facilitatory priming would be demonstrated for word targets with sparse neighbourhoods. Inhibitory priming occurs as the lexical representations with dense neighbourhoods are more precisely tuned, reducing overlap between clusters of similar words and facilitating efficiently and easy access to word targets. However, lexical representations with sparse neighbourhoods have few competing neighbours, resulting in the lexical representation being driven by the letter-level and more broadly tuned to tolerate a fair degree of mismatch. Based on previous research (e.g. Andrews & Hersch, 2010), if orthographic precision provides the best measure of lexical precision, people with high orthographic precision should demonstrate inhibitory priming, while those with low orthographic precision should show facilitatory priming for word targets in the LDT. In word naming, reduced facilitatory priming for word targets should only be observed in people with high orthographic precision in comparison to those with low orthographic precision. In contrast, if phonological precision is a measure of redundancy, priming effects for word targets should be replicated in pseudoword targets (see Table 6.1. for summary of predictions to aid the reader).

Table 6.1. A summary of predictions for the neurotypical population. Upward arrows indicate positive priming effects reflecting facilitation for targets preceded by related primes, relative to unrelated primes. Downward arrows indicate inhibitory priming. The small upward arrows indicate that there is facilitatory priming but the priming effect would be small.

		Dense	Sparse
LDT	High lexical precision		
	Low lexical precision		
Naming	High Lexical precision		
	Low Lexical precision		

Chapters 2 and 3 aimed to assess competition resolution during word processing. The results of the LDT (Chapter 2) revealed that priming effects differ for people with high and low phonological precision, which was also differentially affected by NHD. People with high phonological precision showed inhibitory priming for word targets with dense neighbourhoods but facilitatory priming for word targets with sparse neighbourhoods. People with low phonological precision demonstrated only facilitatory priming for word targets. Together, this indicates that the higher the level of phonological precision, the tighter the bond between orthographic and phonological features, leading to faster lexical retrieval. In this sense, low-level processes (i.e. orthography and phonology) drive the speed of lexical retrieval in reading, aligning with the LQH.

In contrast to word targets, we found that no individual difference component affected the priming effects with regard to rejecting pseudowords. We only observed an interaction of prime lexicality by relatedness: Pseudoword targets preceded by pseudoword primes showed facilitatory priming, while those that followed word primes showed little, if any, priming effects. These findings, and the lack of individual differences contributing to the priming effect, indicate that the inhibitory priming effects are lexical in nature, as such effects were only shown for word recognition, and not for pseudoword rejection. In addition, phonological precision is a measure of not only redundancy but also lexical precision, as this component contributed to the priming effects found for word targets but not pseudoword targets. This aligns with the LQH (Perfetti, 2007, 2017), as redundancy and lexical precision are argued to be mutually dependent.

Chapter 3 used the same participants, paradigm, tests and stimuli but used a visual word naming task rather than an LDT. This was conducted to assess the earlier stages of lexical retrieval and the processes otherwise not (explicitly) included in silent reading, such as a degree of phonological encoding. The main finding was that people with low orthographic precision showed larger facilitatory priming for word targets with sparse neighbourhoods than dense neighbourhoods. They also showed larger facilitatory form priming than people with high orthographic precision. People with high orthographic precision showed larger facilitatory form priming for pseudoword targets preceded by word primes than pseudoword primes, while the converse was demonstrated for people with low orthographic precision. This suggests that the facilitatory priming results from a spelling-to-sound process, as such effects are observed for word and pseudoword targets. Unlike phonological precision, orthographic precision is a measure of redundancy only, contributing to the priming effects for both word and pseudoword targets. This supports Perfetti's (1992, 2007) view that redundancy in skilled readers is more likely to reflect the binding between orthography and phonology in visual word recognition.

When comparing the pattern of results for the LDT (Chapter 2) and naming (Chapter 3) experiments, one of the most intriguing findings was that phonological precision moderated the priming effects for the LDT, while orthographic precision contributed to the priming effects for word naming. Assuming that naming taps into the earlier stages of lexical retrieval while LDT (also) taps into the somewhat later stages (cf. Schilling et al., 1998), this finding can be accommodated straightforwardly in Grainger and Holcomb's (2009) bi-interactive model. In this model (Figure 6.1.), on presentation of a printed word, perceptual features are mapped onto pre-lexical orthographic representations (~ 150ms, letters and letter clusters: O-units) which are then mapped onto whole-word orthographic representations (~250ms, O-words) and at the same time onto pre-lexical and lexical phonological representations via the central interface between orthography and phonology (~250ms-325ms; O ↔ P). Whole-word form representations subsequently activate semantic representations (~400ms, S-units).

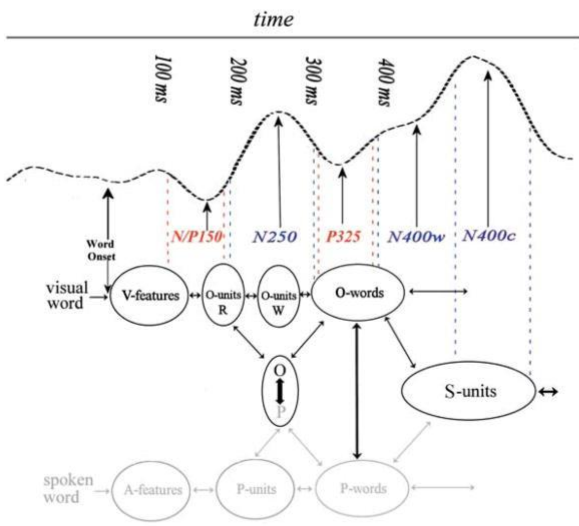

Figure 6.1. The Bi-modal interactive activation model (Grainger & Holcomb, 2009) of word recognition. In this model, orthography (O) and phonology (P) communicate with each other directly at the level of lexical representations (O-words, P-words) and via the sublexical interface (O ↔ P). Semantic representations (S-units) receive activation from lexical-orthographic and lexical-phonological representations. The time frame of each subcomponent is indicated by the dashed lines connecting to the event-related potential wave and the predicted underlying processes.

Competition resolution for reading in the dyslexic population

The PCA for the neurotypical population (Chapters 2 and 3) suggests there are three components that can be individually grouped together as phonology, orthography and semantics. This highlights that these processes are distinct from one another at the subject level in the neurotypical population. In contrast, the PCA for PWD (Chapter 4) showed a different pattern, with orthography, phonology and semantics being part of one single component, suggestive of lexical precision. This result supports the idea of a multiple deficit model (Perry et al., 2019). According to such a model, phonological difficulties do not explain the majority of difficulties manifested in dyslexia (Valdois, Bosse & Tainturier, 2004), but neither does an orthographic nor a semantic impairment. The reading ability in dyslexia depends on the interplay between each individual subcomponent. Perry et al. (2019) found that localist models (i.e. phonological, semantics or orthographic) did not capture the distribution of dyslexic reading scores, arguing that improving one subcomponent can lead to poorer performance in another area. For instance, improving orthographic processing leads to better word reading, irrespective of word type (i.e. nonwords and irregular words), while improving efficiency in either phonology or semantics shows the opposite pattern. Good phonological efficiency leads to good decoding abilities and poor irregular word reading, while developing the processing of semantic information leads to the converse (Perry et al., 2019). Perry et al. concluded these results could be only captured in a multiple deficit account that includes each subcomponent. The current finding and the findings of Perry et al. contradict the pattern predicted by the LQH (Perfetti, 2007). According to the LQH, more skilled readers have more tightly bound and coherent orthographic, phonological and semantic representations, while less skilled readers such as PWD have more distinct representations, indicating reduced coherence of word identities. In contrast, we found that the subcomponent processes for neurotypical readers are distinct, while the subcomponents in PWD are tightly bound and dependent upon each other. The current data suggests a multiple-deficit view, but can also mean that in PWD, these components are not well differentiated, making dyslexia research and the formulation of effective, appropriate and emancipatory interventions challenging. We therefore require a holistic approach in order to understand the pathogenesis of dyslexia.

The predictions for PWD were that, as PWD have poor orthographic and phonological representations, they would perform similarly to people with low orthographic and phonological precision. Alternatively, PWD may perform similarly to the neurotypical population such that PWD with high reading ability should show inhibitory priming or more reduced facilitatory priming effects than those with low reading abilities, aligning with the LQH (see Table 6.2.). However, results from PWD differed from controls to an extent, only partially supporting the LQH.

Table 6.2. A summary of predictions for the dyslexic population. Upward arrows indicate positive priming effects reflecting facilitation for targets preceded by related primes, relative to unrelated primes. Downward arrows indicate inhibitory priming. The small upward arrows indicate that there is facilitatory priming but the priming effect would be small. The equal sign indicates that there is little, if any, priming effect. The lexical precision component reflects the predictions made from the LQH, while the group predictions indicate that they are matching those predicted by the author based on the findings for people with low phonological and orthographic precision (Chapters 2 and 3). Green ticks indicate which predictions were confirmed for each task.

		Dense	Sparse
LDT	High lexical precision	↓ ✓	↑ ✓
	Low lexical precision	= ✓	= ✓
	Group	↑	↑
Naming	High Lexical precision	↑ (small)	↑ (small)
	Low Lexical precision	↑ (small)	↑
	Group	↑ (small) ✓	↑ ✓

The findings for the LDT were consistent with the LQH. In general, PWD with low lexical precision showed little, if any, priming effects, while those with high lexical precision demonstrated inhibitory priming for word targets, except for those with sparse neighbourhoods preceded by pseudoword primes. Concerning pseudoword targets, PWD with high lexical precision showed little, if any, priming effects, whereas those with low lexical precision demonstrated facilitatory form priming. These findings indicate that PWD who have high lexical precision are more likely to use the direct lexical route, thus facing lexical competition between the prime and target and demonstrating little, if any priming effects. However, PWD who have low lexical precision process the pseudoword or word prime and target at the sublexical level.

Results of word naming and pseudoword naming in PWD were inconsistent with the LQH but aligned with the findings shown in Chapter 3 for neurotypical participants with low orthographic precision. For example, PWD showed smaller facilitatory priming for word targets with dense neighbourhoods than those with sparse neighbourhoods. In addition, PWD showed smaller facilitatory priming for pseudoword targets preceded by pseudoword primes than word primes. This contradicts the finding that orthographic precision is different from lexical precision. However, orthographic precision is solely a measure of redundancy as shown only in the naming task, while the component of lexical precision includes redundancy, as well lexical precision. This indicates that lexical processes in PWD are preserved. This is consistent with Ziegler and Goswami (2005), who argued that children with dyslexia do not perform worse than reading-age matched children during tasks that assess lexical-orthographic processes such as word recognition. However, it important to mention that orthographic processing at the sublexical level is impaired in PWD, as lexical precision did not contribute to the naming task. Given this, there may be multiple deficits at the lexical level, but the pathogenesis of dyslexia may occur at the early stages of lexical retrieval (i.e. orthographic precision and phonological decoding).

The dyslexic population and its relationship to childhood stuttering

Finally, the poor articulatory abilities in PWD may result from co-occurrence with an articulatory difficulty such as stuttering. Chapter 5 assessed whether the articulatory difficulties resulted from childhood stuttering or were a genuine impairment in PWD. We found that 34% of PWD had stuttered during childhood. This was moderated by the severity of dyslexia: 15% of people with mild dyslexia stuttered during childhood, whilst 47% of people with severe dyslexia stuttered during childhood. The second finding was that PWD and PWS showed no differences on any measure that assessed phonological processing. In conclusion, our results indicate that there may be an underlying phonological impairment in both conditions, though further research is needed to assess the nature of the phonological deficit. Childhood stuttering may have contributed to the findings related to PWD (Chapter 4) but this was not possible to assess due to small sample size (see limitations).

Limitations

The findings presented in this thesis should be discussed within the context of a number of limitations, together with possibilities of further investigation. The participants in the thesis were young adults and PWD attending university. Young adults are deemed to be at the zenith of their cognitive abilities (see review by Mortensen, Meyer & Humphreys, 2006) and, as discussed in Chapter 2, lexical representations change with age. For example, children mature and their reading is more likely to depend on orthographic than phonological representations, allowing their representations to be more lexical than sublexical in nature (Perfetti, 1992). It is therefore unclear whether the present findings with young adults can be generalised to different age groups.

A second question concerns to what extent the current findings can be applied to PWD from various social and educational backgrounds. Do PWD who attend university differ from those who are not in higher education? If they do differ, is this difference quantitative or qualitative? A quantitative difference would predict that people with high lexical precision are more likely to attend university than those with low lexical precision. If the difference is qualitative, then the findings from this line of research may not be directly applicable to PWD from different educational backgrounds. Nevertheless, the findings of the current study are provided within the open science framework, allowing the current dataset to be used for multi-site collaboration and meta-analyses to enable further development in the research of dyslexia. This research is important in that it can offer a theoretical basis for the relationship between speech and reading and the importance of phonology in both areas.

In this thesis, the assessment of dyslexia depended on several phonological, orthographic and semantic tasks. However, reading aloud has been found to be more influenced by articulatory properties such as onset complexity and voicing (Ferrand et al., 2011; Rastle & Davis, 2002). It could be more beneficial to include the Stuttering Severity Index Scale (SSI; Riley, 1994) to assess the severity of stuttering and articulatory processes in the control and dyslexic populations. In the current study, we only used the SSI (i.e. a measure to assess speech fluency) for PWS. However, we found that the TOWRE, which was used with PWD and to assess reading fluency in controls, was strongly correlated with the SSI (> .60) (Elsherif, Wheeldon, & Frisson, under review). In addition, the TOWRE has been standardised across many languages and cultures, confirming its validity. However, future studies should consider measuring the severity of stuttering at the point of testing, using the SSI to assess the articulatory properties of lexical quality, together with the importance of individual differences in connected speech.

In addition, the small sample sizes limit the generalisability of the results obtained in the studies with PWD and PWS. Conclusions from these studies, therefore, are only suggestive and should be cautiously interpreted. Although there are 50 PWD and 30 PWS included here (Chapters 4 and 5, respectively), having a larger number of participants would improve the power of the findings. Research with clinical populations is frequently constrained by small sample sizes. Work that has been carried out with PWS and PWD mainly includes small numbers of participants, and there are several reasons for this. Stuttering is a rare condition (1%), PWS can face social ostracism and ridicule, leading to social anxiety (e.g. O'Brian et al., 2011) and there are fewer PWD and PWS who attend higher education due to accessibility issues (e.g. O'Brian et al., 2011; Pino & Mortari, 2014). Larger studies are therefore required to assess the extent to which our findings are genuine or result from a sampling error. However, the effect sizes obtained (e.g. *d* ranging from 0.51 to 1.54 in PWD and 0.54 to 1.78 in PWS) were medium to high, and the power for the main finding of Chapter 5 was extremely high - around 0.9. This suggests that despite the small numbers used here, power remained high, making the results robust.

Conclusions

The thesis assessed the individual differences underlying competition resolution for visual word production and recognition in the neurotypical and dyslexic populations. Conceptually, the overall aim of this thesis was to contribute to the LQH (Perfetti, 2007, 2017). I examined a relatively large number of neurotypical adults and adults with dyslexia. In Chapters 2 and 3, I reported the results of masked priming experiments that tested the effect of NHD, relatedness and prime lexicality, together with a PCA that combined certain components. Critically, even for my neurotypical population, individual differences had significant effects on the priming patterns, together with the lexical variable (i.e. NHD). In Chapter 4, we extended this research to PWD. We found that there was an independent factor that combined orthography, phonology and semantics defined as lexical precision. The component of lexical precision affected NHD in word recognition but not visual word naming. Finally, in Chapter 5, we compared PWD and PWS and reported that dyslexia and stuttering are more similar than once presumed. My research demonstrates that simple measures of only phonology, orthography or semantics are unlikely to capture the full picture of reading in the neurotypical population and a suite of individual difference measures is required. In addition, assessing phonology, orthography and semantics is the best way forward to capture the whole model of reading distribution, especially in PWD. We are far from fully understanding the effects of these individual subcomponents and their relationship with competition resolution in reading. However, using a suite of individual difference measures will move us forward.

Future research should address these issues in detail. We should explore whether the effect of orthographic precision shown in visual word naming is an orthographic or an early perceptual effect that is peripheral to word identification. Put simply, there may be some early and low-level system that notices the visual difference between the prime and target that may be relevant to the attention system, but not to the word during visual word naming. Chauncey, Holcomb and Grainger (2008) showed that changing font style affected repetition priming in the N150 component and windows up to 200ms but not the later component such as N250. The present findings may have captured the combined effects of perceptual and orthographic mechanisms, which will need to be disentangled. It has been found that less skilled deaf readers were more likely to show more facilitation as a result of physical overlap between the prime and target words (Sigut, Vergara-Martinez & Perez, 2019), suggesting that deaf readers were more influenced by visual factors during online reading. They concluded that skilled deaf readers showed smaller priming effects, as lexical feedback modulated orthographic processing to a greater extent than in less skilled deaf readers. It could therefore be predicted that people with high orthographic precision would be less affected by the physical similarity between the prime and target than people with low orthographic precision. This results in the former showing smaller facilitatory priming, as people with high orthographic precision have better lexical feedback that modulates orthographic processing, allowing them to ignore the perceptual processes for visual word recognition.

Another line of future research is to assess the process of competition resolution in a longitudinal manner to evaluate whether competition resolution is impaired in PWD, providing us a clearer insight into the pathogenesis of dyslexia. A longitudinal design is vital to assess the developmental course of dyslexia to differentiate between the components that improve during development and those that worsen as academic demands increase. This should allow us to locate the differences between good and poor readers and respond to questions such as do children who stutter who share a phonological impairment with children with dyslexia (as shown in Chapter 5 with adults who stutter and adults with dyslexia) become poor readers? If we find a similarity between the phonological processing difficulties experienced by PWS and PWD, this will indicate that interventions used for PWD can be implemented for PWS and vice versa. If differences in certain components of phonological processing are experienced by both populations, then a different component of phonology may contribute to competition resolution for reading development and speech fluency. Although the findings of the current study provide an introduction to how competition in word recognition and production is resolved in adults, investigating this pattern in a longitudinal manner may provide effective methods of intervention for struggling readers and can help us understand the pathogenesis of dyslexia.

In conclusion, the study provides an important contribution to how LQ contributes to competition resolution in visual word naming and visual word recognition. A suite of individual difference measures, including assessments of phonology, semantics and orthography, allow researchers to understand the components that drive competition resolution in visual word recognition and production. The findings of this study suggest that NHD, together with prime and target lexicality, affect competition resolution, and these effects vary according to the components of orthographic and phonological precision for neurotypical individuals and the component of lexical precision for PWD. The data for the neurotypical population supports the LQH, while the data for the dyslexic population only partially supports the LQH. This work makes an important contribution to methods of identification and intervention for adults with dyslexia.

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APPENDICES

Appendix A

Table A1. Target Words and Primes Used.

High N					Low N				
Target	Related word	Unrelated word	Related pseudoword	Unrelated pseudoword	Target	Related word	Unrelated word	Related pseudoword	Unrelated pseudoword
BANE	bake	slam	bame	slan	BLOB	blot	trip	Blod	trin
BANG	bank	ride	barg	rine	BRAT	bran	scan	Scad	braf
BARD	barn	lime	barl	lise	BULB	bulk	drug	Drun	bulf
BASS	base	tide	baws	tite	CLAW	clay	trot	Clav	trok
BEAD	bean	coke	beal	cose	CRAG	crab	mule	Craq	mune
BEAK	beat	lane	beaf	lare	CUTE	cube	stab	Cude	staq
BELT	bell	race	beld	rark	DRUM	drug	snow	Drun	snod
BIDE	bile	rang	bife	rask	FIST	fish	step	fisk	ster
BOLL	bold	dine	bolk	dise	FLAN	flag	prey	flav	preg
BOOT	boon	save	bood	sape	FLOG	flop	clay	floq	clav
CART	card	pile	cark	pire	FUNK	fund	plot	furk	ploq
CORD	corn	wave	cort	wafe	GRAM	grab	quid	graw	quin
COVE	coke	barn	cose	barl	GRIM	grip	noon	gris	nool
DICE	dine	pink	dise	pilt	MESH	mess	snap	mesk	snay
FADE	fake	heat	fafe	heak	MUSE	mule	snug	mune	snuf
FILE	fill	bell	fite	beld	NEWT	news	bran	nemt	braf
HEAL	heat	bake	heak	bame	NOOK	noon	prop	nool	prot
LACE	lane	fill	lare	fite	PLOY	plot	grip	ploq	gris
LICE	lime	bean	lise	beaf	PLUM	plug	crab	plur	craq
LICK	link	fake	lirk	fafe	PRAM	pray	news	pras	nemt
MILL	mile	sole	milt	sone	PREP	prey	blot	preg	blod
MOLE	mode	bank	barg	moke	PRIME	price	sleep	prixe	sleef
PEAR	peak	sang	pean	sark	PROD	prop	stub	prot	stum
PEEK	peep	vile	peet	vire	QUIZ	quid	slab	quin	slaq
PILL	base	pile	pilt	baws	SCAB	scan	fish	scad	fisk
PINE	pink	tall	pire	tade	SKIP	skin	plug	skig	plur
RACK	race	mode	rark	moke	SLAY	slab	pray	slaq	pras
RANK	rang	mile	rask	milt	SLEEK	sleep	price	sleef	prixe
RAVE	rare	peep	rase	peet	SNAG	snap	cube	snay	cude
RICE	ride	beat	rine	beal	SNOT	snow	thud	snod	thup
SAGE	save	link	sape	lirk	SNUB	snug	tube	snuf	tuse
SANK	sang	bold	sark	bolk	STAG	stab	twin	staq	twip
SEAL	seat	corn	sead	cort	STEM	step	mess	ster	mesk
SLAM	slap	rare	slan	rase	STUN	stub	grab	stum	graw
SORE	sole	tear	sone	tead	THUG	thud	skin	thup	skig
TALE	tall	card	tade	cark	TRIM	trip	yard	trin	yarc
TEAL	tear	bile	tead	bife	TROD	trot	bulk	trok	bulf
TILE	tide	seat	tite	sead	TUNE	tube	flag	tuse	flav
VINE	vile	boon	vire	bood	TWIG	twin	fund	twip	furk
WADE	wave	peak	wafe	pean	YARN	yard	flop	yarc	floq

Table A2. Target Pseudowords and Primes Used.

	High N					Low N			
Target	Related word	Unrelated word	Related pseudoword	Unrelated pseudoword	Target	Related word	Unrelated word	Related pseudoword	Unrelated pseudoword
BEED	beer	tape	beek	tare	BLOON	blood	mouth	bloor	mouks
BINK	bind	root	bint	roon	BLUK	blur	disc	blut	dirm
DANT	dart	ripe	dast	rike	BRAX	brag	skim	brac	skix
DARS	dark	wear	dass	wead	BRIN	brim	club	bris	clud
FAGE	fate	mock	fase	mort	CALK	cask	moth	cald	moft
FALE	fare	wing	fane	wist	CLUS	clue	drop	clux	drot
HAID	hail	luck	hait	lusk	CLUT	club	scar	clud	scak
HANE	hare	beer	hame	beek	DERK	desk	plop	dert	plom
HASE	hate	nick	hace	nind	DIRC	disc	salt	dirm	swav
HOOM	hook	wide	hoon	wite	DISP	dish	brag	dirp	brac
LASE	lake	mice	lave	mide	DRAD	drag	blur	draf	blut
LOTE	lore	dart	loke	dast	DRAS	draw	vice	drax	vipe
LUNK	luck	wine	lusk	wime	DROB	drop	swim	drot	swid
MAIT	mail	lore	mant	loke	DUSP	dusk	clue	dunp	clux
MIFE	mice	sand	mide	sast	FROP	frog	glue	froy	glus
MOOL	moon	wage	mook	wate	GLUR	glue	risk	glus	rild
MORK	mock	vest	mort	vell	GOWS	gown	swap	goms	ralt
NEAK	neat	mail	mant	nead	MAWK	mask	draw	mazk	drax
NINK	nick	fate	nind	fase	MOTT	moth	dish	moft	dirp
PASK	pass	bind	pash	bint	MOUTS	mouth	blood	mouks	bloor
PERS	peas	lake	pess	lave	NUBE	nude	wool	nule	woox
POLT	port	ward	pold	warl	PLAS	plan	cask	plaw	cald
RALE	rake	test	rade	telt	PLOK	plop	nude	polf	nule
RIBE	ripe	tack	rike	tass	PLON	plod	dusk	plom	dunp
ROOS	root	tuck	roon	tunt	RAKT	raft	tree	ralt	tred
SANT	sand	hook	sast	hoon	RILK	risk	brim	rild	bris
SARE	sale	hail	sace	hait	SALF	salt	tram	sald	trax
SEET	seed	rake	seel	rade	SCAF	scar	gown	scak	goms
SELD	sell	hare	selt	hame	SKIR	skim	frog	skix	froy
TACS	tack	port	tass	pold	SLIN	slim	zeal	slic	zead
TASE	moon	tape	mook	tare	SPAV	span	desk	spaw	dert
TEFT	test	pass	telt	pash	STEB	stew	drag	stek	draf
TUNK	tuck	hate	tunt	hace	SWAC	swap	mask	swav	mazk
VELT	vest	dark	vell	dass	SWIB	swim	plan	swid	plaw
WALE	wage	seed	wate	seel	TASP	task	plod	tanp	plof
WARK	ward	sell	warl	selt	TRAV	tram	raft	trax	sald
WEAT	wear	fare	wead	fane	TRET	tree	span	tred	spaw
WICE	wine	peas	wime	pess	VIGE	vice	stew	vipe	stek
WIKE	wide	neat	wite	nead	WOOR	wool	task	woox	tanp
WINT	wing	sale	wist	sace	ZEAK	zeal	slim	zead	slic

Appendix B

An exploratory factor analysis conducted with the individual difference measures without combining them in the neurotypical population.

Factor 1 Reading Fluency	Loading value	**Factor 2** Lexical-semantic processing	Loading value	**Factor 3** Print exposure	Loading value	**Factor 4** Phonological working memory	Loading value
RLN	0.82	EVT	0.73	ART	0.92	Memory for digits	0.82
TOWRE-P	0.81	GSRT	0.73	TRT	0.91	Nonword repetition	0.80
TOWRE-S	0.76	BPVS	0.71	Spelling	0.51		
		Phoneme Reversal	0.57				
% variance	*0.18*		*0.17*		*0.16*		*0.13*
Cumulative variance	*0.18*		*0.35*		*0.51*		*0.64*

Note. RLN = Rapid Letter Naming; TOWRE-P = Test of Word Reading Efficiency phonemic decoding; TOWRE-S = Test of Word Reading Efficiency sight word reading; EVT = expressive vocabulary test; GSRT = Gray Silent Reading Test; BPVS = British Picture Vocabulary Scale; ART = Author Recognition Test; TRT = Title Recognition Test.

Appendix C

Example R codes in the neurotypical population – of the minimal model reported in the results for word target and pseudoword target. In example 1, lexical decision latencies is regressed as a function of the prime lexicality (word or pseudoword), relatedness (related or unrelated) and NHD (dense or sparse), along with phonological precision and orthographic precision. In the model, the intercept values of subjects, items and 'other items' variables are included as random random effect. In example 2, lexical decision latencies for pseudoword targets is regressed as a function of prime lexicality (word or pseudoword) and relatedness (related or unrelated), orthographic precision and phonological precision. In the model, the intercept values of subjects, items and 'other items' variables are included as random effect. In example 3, naming latencies for word targets is regressed as a function of the prime lexicality (word or pseudoword), relatedness (related or unrelated) and NHD (dense or sparse), along with phonological precision and orthographic precision. In the model, the intercept values of subjects, items and 'other items' variables are included as random effects. In example 4, naming latencies for pseudoword targets is regressed as a function of NHD (dense or sparse), prime lexicality (word or pseudoword) and relatedness (related or unrelated), orthographic precision and phonological precision. In the model, the intercept values of subjects, items and 'other items' variables are included as random effect.

(1) **Word target for LDT in neurotypical population**

```
lmer(log(RT) ~ 1 + CPhonological_precision * relatedness * NHD + prime
lexicality * relatedness + COrthographic_precision + (1 + NHD | subject) +
(1|item), data = X, REML = FALSE, lmerControl(optimizer = 'bobyqa', optCtrl
= list(maxfun=20000)))
```

(2) **Pseudoword target for LDT in neurotypical population**

```
lmer(log(RT) ~ 1 +NHD + COrthographic_precision +
CPhonological_precision + relatedness * primetype + (1 + NHD +
relatedness | subject) + (1|item), data = X, REML = FALSE, control =
lmerControl(optimizer = 'bobyqa', optCtrl = list (maxfun = 20000)))
```

(3) **Word target for naming in neurotypical population**

```
lmer(log(RT) ~ 1 + COrthographic_precision * relatedness * NHD * prime
lexicality + CPhonological_precision + (1 + NHD + relatedness | subject) +
(1|item), data = X, REML = FALSE, lmerControl(optimizer = 'bobyqa', optCtrl
= list(maxfun=20000)))
```

(4) **Pseudoword target for naming in neurotypical population**

```
lmer(log(RT) ~ 1 + COrthographic_precision * prime lexicality * relatedness
+ CPhonological_precision + relatedness + NHD * relatedness (1 + NHD +
relatedness | subject) + (1|item), data = X, REML = FALSE, control =
lmerControl(optimizer = 'bobyqa', optCtrl = list (maxfun = 20000)))
```

Appendix D

An exploratory factor analysis conducted with the individual difference measures without combining them in PWD.

Factor 1 Lexical precision	Loading value	**Factor 2** Reading Fluency	Loading value	**Factor 3** Phonological working memory	Loading value
EVT	0.84	TOWRE-P	0.79	Memory for digits	0.84
TIWRE	0.80	RLN	0.77	Nonword repetition	0.54
ART	0.78	TOWRE-S	0.77		
GSRT	0.67				
BPVS	0.67				
Spelling	0.54				
Nonword repetition	0.52				
% variance	*0.33*		*0.18*		*0.12*
Cumulative variance	*0.33*		*0.51*		*0.63*

Note. EVT = expressive vocabulary test; TIWRE = Test of Irregular Word Reading Efficiency; ART = Author Recognition Test; GSRT = Gray Silent Reading Test; BPVS = British Picture Vocabulary Scale; TOWRE-P = Test of Word Reading Efficiency phonemic decoding; RLN = Rapid Letter Naming; TOWRE-S = Test of Word Reading Efficiency sight word reading

Appendix E

Example R codes in the dyslexic population – of the minimal model reported in the results for word target and pseudoword target. In example 1, lexical decision latencies is regressed as a function of the prime lexicality (word or pseudoword), relatedness (related or unrelated) and NHD (dense or sparse), along with lexical precision. In the model, the intercept values of subjects, items and 'other items' variables are included as random effect. In example 2, lexical decision latencies for pseudoword targets is regressed as a function of NHD (dense or sparse) prime lexicality (word or pseudoword) and relatedness (related or unrelated), lexical precision. In the model, the intercept values of subjects, items and 'other items' variables are included as random effect. In example 3, naming latencies for word targets is regressed as a function of NHD (dense or sparse), relatedness (related or unrelated) and NHD (dense or sparse), along with lexical precision. In the model, the intercept values of subjects, items and 'other items' variables are included as random effects. In example 4, naming latencies for pseudoword targets is regressed as a function of prime lexicality (word or pseudoword) and relatedness (related or unrelated), lexical precision. In the model, the intercept values of subjects, items and 'other items' variables are included as random effect.

---

(1) **Word target for LDT in dyslexic population**

```
lmer(log(RT) ~ 1 + CLexicalprecision * NHD * primetype * relatedness + (1 +
NHD | subject) + (1|item), data = X, REML = FALSE, lmerControl(optimizer =
'bobyqa', optCtrl = list(maxfun=20000)))
```

(2) **Pseudoword target for LDT in dyslexic population**

```
lmer(log(RT) ~ 1 + CLexicalprecision * NHD * primetype * relatedness + (1 +
NHD | subject) + (1|item), data = X, REML = FALSE, lmerControl(optimizer =
'bobyqa', optCtrl = list(maxfun=20000)))
```

(3) **Word target for naming in dyslexic population**

```
lmer(log(RT) ~ 1 + CLexical_precision + relatedness * NHD + NHD * prime
lexicality + (1 + NHD | subject) + (1|item), data = X, REML = FALSE,
lmerControl(optimizer = 'bobyqa', optCtrl = list(maxfun=20000)))
```

(4) **Pseudoword target for naming in dyslexic population**

```
lmer(log(RT) ~ 1 + CLexical_precision + prime lexicality * relatedness (1 +
NHD | subject) + (1|item), data = X, REML = FALSE, control =
lmerControl(optimizer = 'bobyqa', optCtrl = list (maxfun = 20000)))
```
