VISUAL AND PHONOLOGICAL PROCESSING IN DEVELOPMENTAL DYSLEXIA: A CROSS-LINGUISTIC INVESTIGATION

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DD = Developmental Dyslexia

DRC= Dual Route Cascaded model

GPC = grapheme-phoneme conversion

RAN = rapid automatised naming

RT = Reaction Times

TDR= Typical Developing Readers

VSWM = Visuo-Spatial Working Memory

WLE = Word Length Effect

Abstract

This thesis aimed to investigate the extent to which visual processing is impaired in individuals with developmental dyslexia (henceforth DD) across orthographies varying in orthographic transparency. Contrasting the prevailing account, it was proposed that a phonological deficit *per se* may not to be sufficient to explain the difficulties shown by individuals with reading disorders.

Chapter 2 (Study 1) examined the reading performance of a group of adult participants with DD which was contrasted with that of a group of typical developing readers (TDR) in an opaque/inconsistent orthography. The word length effect (WLE), slower reading of lengthier words, a phenomenon which has received more attention in DD in transparent than in opaque orthographies, was investigated. The results revealed that a WLE indexed as reading reaction times (RT) persisted in DD even in a population of highly educated individuals. This evidence suggests that speed might be a more sensitive measure of reading difficulties than reading accuracy when assessing reading by DDs, even in opaque orthographies such as English. Moreover, such an effect might be related to impaired visual processing that in turn affected fast visual word recognition in the DD sample.

Chapter 3 (Study 2) explored the contention of visual processing impairments in DD. Visual processing and visuo-spatial working memory (VSWM) were evaluated in a group of English individuals with DD, whose performance was contrasted to that of TDRs. Two visual matching tasks adopting visual stimuli that differed in the degree of complexity and similarity, and three VSWM tasks were administered to each participant. In line with the dominant hypothesis of phonological deficits in DD, phonological processing was evaluated using the digit span task. Results revealed impaired visual and phonological processing in DD participants. Furthermore, in

a discriminant function analysis, conducted to establish which tasks most effectively discriminate between DD and TDRs, group membership was predicted by one visual and one phonological task. This evidence provides support for the contention that the processing of both visual and phonological stimuli may be deficient in DD.

In Chapter 4 (Study 3) a direct comparison between English and Italian individuals with DD and TDRs was conducted on visual and phonological processing, with the view to investigate differences in visual processing in DD in the two orthographies. The performance of the Italian DD and the English DD samples was compared to each other and with that of two groups of TDRs by using the two visual matching tasks described in Study 2 and the digit span task. The results showed that the two TDR groups did not differ from each other in all tasks. Unsurprisingly, they outperformed both DD groups. More critically, the Italian DD group performed worse than the English DD group on the visual matching tasks, in particular in the visually complex conditions. No significant difference was found in the phonological task between the two DD groups.

Taken together, the findings of this thesis confirm a) phonological processing is pivotal in reading disability irrespective of orthographic consistency/transparency; b) phonological processing impairments alone do not fully account for reading difficulties when visual processing deficits are evident across languages; c) visual processing deficits vary according to orthographic consistency with readers of a consistent/transparent orthography being more impaired in visual processing than readers of an inconsistent/opaque orthography.

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over these years, I eventually managed to complete my PhD and I am so proud of myself. Perhaps for the very first time in my life.

Per aspera ad astra

1 Introduction

1.1 Skilled reading

Reading is a crucial ability in everyday life and the basis to acquire knowledge about the world around us. Despite its acknowledged importance, low literacy skills still represent a critical and persistent challenge around the world. Even in developed countries, some individuals do not attain a level of reading performance that allows them to participate effectively in society (Organisation for Economic Cooperation and Development, 2016).

The importance that reading achievement has in life has fortified the very considerable body of research investigating how people learn to read. Indeed, even though reading seems to be a heritable trait (see Olson, Keenan, Byrne, & Samuelsson, 2014 for a discussion of the interaction between genes and the enviroment in reading acquisition), it is undoubtedly also a learned skill that requires practice and formal instruction for successful acquisition. A child aiming to master reading must learn how to analyse the printed forms of the words encountered (Castles, Rastle, & Nation, 2018a).

Achieving reading mastery is therefore portrayed as a complex developmental progression, with some authors postulating that children move through different "stages" to accomplish fluent reading (see e.g., Ehri, 2005; Frith, 1985). In this scenario, the young reader transits from "reading" very familiar words by using salient visual features that act as cues to word identity (e.g., double f in *giraffe* see e.g., Frith, 1985) to learning the correspondence between the letters in the written form and the sounds of the spoken form (grapheme-phoneme conversion or GPC), which enables them to apply such knowledge to read unfamiliar words (i.e., the alphabetic phase, see Ehri, 2005; Frith, 1985; although see Stuart & Coltheart, 1988 for a different perspective).

Despite the claim posited by the proponent of the stage theories that reading development can be conceptualised as a sequence of stages, however Stuart and Coltheart (1988) argued that not all children pass through the same sequence of stages. Furthermore, they demonstrated that phonological skills could play a role since the very first stage of learning to read (Stuart & Coltheart, 1988).

Phonological skills are therefore considered essential for learning to read. Much evidence has demonstrated that children's knowledge of the phonological structure of language is a good predictor of early reading ability (Caravolas, Volín, & Hulme, 2005; Goswami, 2002; Goswami & Bryant, 2016 although see Castles & Coltheart, 2004) and it is usually accomplished by children early in their reading journey for example by the end of the first school year (athough with some exceptions across orthographies see Seymour, Aro, & Erskine, 2003).

The umbrella terminology of phonological skills usually encompasses phonological awareness, verbal short-term/working memory and letter knowledge, which are three of the most widely studied measures of children's phonological skills (Hulme & Snowling, 2013; Melby-Lervåg, Lyster, & Hulme, 2012; Snowling & Melby-Lervåg, 2016).

Phonological awareness is a metalinguistic ability that supports the elaboration of the linguistic structure of words. This skill enables readers to recognise, discriminate, analyse and manipulate oral sounds (Ziegler & Goswami, 2005). Thus, it refers for example, to the inclination of the reader to focus on phonemes, reducing words into smaller segments which are converted into the correspondent sounds, or phonemes (Vellutino, Fletcher, Snowling, & Scanlon, 2004). A component of phonological awareness is phonemic awareness. This is the ability to process phonemes, that is, the smallest units of linguistic systems.

The relationship between phonological awareness and word decoding is well established (Neri & Pellegrini, 2017; Stahl & Murray, 1994; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Ziegler & Goswami, 2005). An extensive body of studies highlighted that good phonological awareness is predictive of skilled reading (e.g., Castles & Coltheart, 2004), whereas, in contrast, reduced phonological awareness proficiency characterises poor readers (Ziegler & Goswami, 2005). Moreover, meta-analyses indicated that children with word reading difficulties had large phonemic awareness deficits compared to typical age matched controls and reading age matched controls (see Melby-Lervåg et al., 2012 for details).

Letter-sound knowledge, another important component of phonological skills, refers to the appreciation that letters in printed words map onto phonemes in spoken words (see Hulme & Snowling, 2013). Longitudinal studies have demonstrated a predictive role of letter-sound knowledge in reading even when phonological awareness is controlled (Elbro, Borstrøm, & Petersen, 1998; Muter, Hulme, Snowling, & Stevenson, 2004).

Verbal short-term/WM, where verbal information is stored for a limited amount of time, (Baddeley, 1986; Baddeley & Hitch, 1974, 2000) is the third example of the phonological skills examined in this section. It has been demonstrated that efficient operation of phonological codes in memory is necessary for various phonological activities, such as segmenting and blending sounds in spoken words, processes involved in learning to read (see Baddeley, 1986; Gathercole & Baddeley, 1993; Melby-Lervåg et al., 2012). Moreover, verbal short-term memory tasks, such as digit and word span, are probably the most widely used measures of implicit phonological processing (i.e., access to phonological codes without any explicit meta-cognitive reflection on, or awareness of, the sound structure of spoken words see Melby-Lervåg et al., 2012).

Phonological skills are therefore important as they enable children to map orthographic units (letters) onto speech sounds (phonemes) and thus decode unfamiliar words (Elliot & Grigorenko, 2014; Share, 2004). It also allows children to build up an internal lexicon, which in turn leads to the rapid recognition of familiar words (e.g., Richlan, 2014). However, the mapping between letters and their sounds, although important even in skilled readers, is not sufficient for fluent reading, especially of irregular words (i.e., words with an inconsistent letter-sound mapping, e.g., *have*, *pint*). As children progress toward becoming skilled readers, the reliance on alphabetic decoding decreases (e.g., Spinelli et al., 2005; Zoccolotti et al., 2005), although such a strategy is still employed by skilled readers when they come across unfamiliar words or nonwords (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). The transition from the phonological decoding of unfamiliar words to rapid word recognition is defined by some authors as orthographic learning (for a recent review see Castles, Rastle, & Nation, 2018b).

The most influential theory regarding the shift to the orthographic recognition of words has been proposed by Share and is referred to as the self-teaching hypothesis (Share, 2008b). Share advanced the hypothesis that a combination of alphabetic decoding (which he defined as the "*sine qua non*" of reading acquisition) and repeated exposure to the written form of the word allows children to self-teach through their independent reading (Share, 1999).

The fact that skilled reading requires more than just alphabetic decoding has been suggested by models of skilled reading. Some of these models, describing the mechanisms underpinning reading are expressed as computer programs known as computational models. Two of the main computational models employed to describe the mechanisms involved in orthographic recognition and reading aloud are the Dual-Route Cascaded model (hereafter DRC Coltheart et al., 2001) and the triangle model (Plaut, McClelland, Seidenberg, & Patterson, 1996), which are reviewed below.

1.2 The DRC model

In the DRC model (Coltheart et al., 2001), reading is generally assumed to involve two major processes or “routes” the lexical non semantical route and the sub-lexical route (Figure 1.1). First, one can access reading through the lexical non semantic route. Following this route, the stored word pronunciations is activated in the “phonological lexicon” following activation from the “orthographic lexicon”. Once activated, the phonological lexicon then activates the whole word needed for speech. This lexical process is necessary when reading words with ambiguous or irregular spellings such as the English word “*colonel”*. However, the process fails with unfamiliar words and nonwords since these items do not have a stored representation in the orthographic lexicon.

Second, reading can occur via a sub-lexical grapheme-to-phoneme (i.e., letter-to-sound) conversion process (GPC), which allows individuals to read unfamiliar words with a regular grapheme-phoneme correspondence and nonwords (e.g., *plur*), by converting graphemes into phonemes in a serial left-to-right fashion. In contrast to the lexical process, the sub-lexical process can generate plausible pronunciations for regular words or phonologically plausible nonwords but will produce regularisation errors for irregular words (e.g., colonel becomes “colernel”; yacht “yatched”). According with DRC model a third route has been postulated, called lexical semantic route. However, this route has not been implemented (see Coltheart et al., 2001).

It is worth noting that the DRC model of reading was primarily developed to explain cognitive processes involved in reading English by skilled readers as well as impaired reading by neurological patients due to brain damage (Coltheart et al., 2001). However, its proponents argued it offers an account to explain developmental reading disorders as well and it was employed to simulate developmental reading difficulties (Coltheart, 2015; Coltheart et al., 2001; Ziegler et al., 2008).

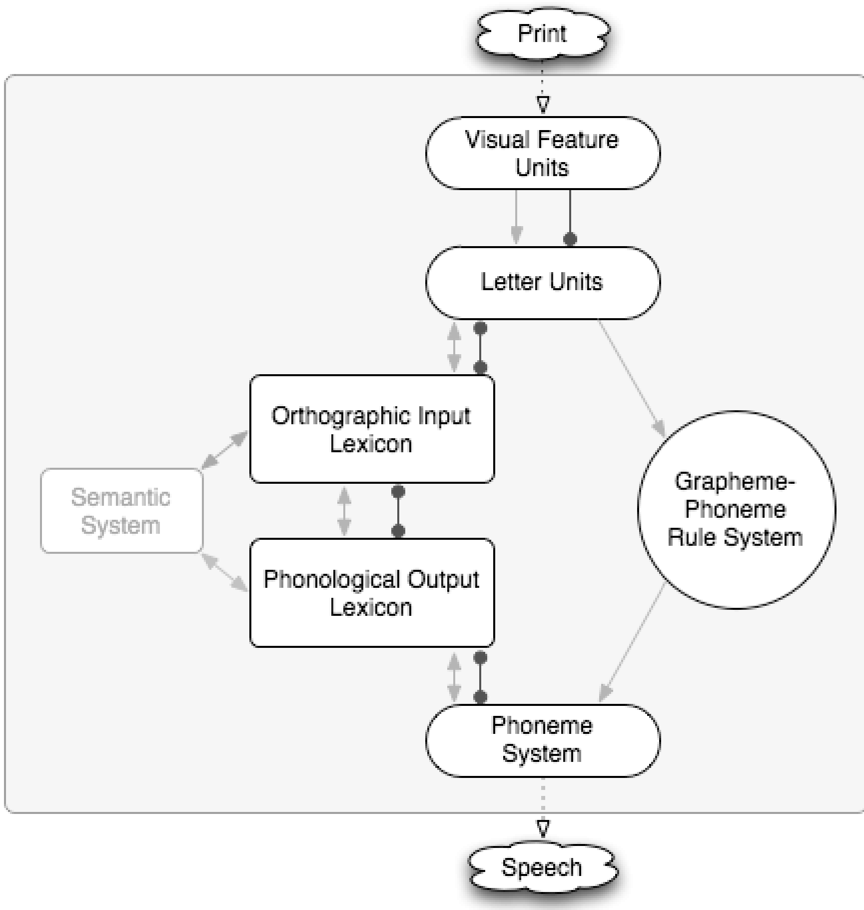

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Figure 1.1. The DRC model (Coltheart et al., 2001)

The primary systems hypothesis proposes that reading is underpinned by domain-general systems recruited in a variety of tasks within that particular domain. The triangle model, an instantiation of this approach implemented in a connectionist network, will be reviewed in the next section.

1.3 The triangle model

An alternative approach to the DRC model, is the primary systems hypothesis (Patterson & Lambon Ralph, 1999). The primary systems hypothesis proposes that reading is underpinned by a triangulate of domain-general neurocognitive systems: vision, phonology and semantics (Patterson & Lambon Ralph, 1999; Plaut et al., 1996). The triangle model (Plaut et al., 1996; Seidenberg & McClelland, 1989) is an instantiation of this approach.

In this view, a permutation of the three systems supports various different linguistic and non-linguistic activities. Consequently, in relation to reading, the notion of domain generality within the primary system hypothesis conceives that more general processes support reading-based tasks. For instance, letter identification is critical for reading and provides input to the processes that allow us to recognise written words – a small and easily confusable set of visual symbols. In this view, letters are simply a particular class of visual stimuli, that, like other visual objects are made up of constituent features (e.g., lines, curves, intersections etc.) that describe the letter's shape. These features are not letter specific and are processed by the visual system to support whole word reading. Therefore, in contrast to the DRC, it does not include reading-specific representations (the lexicons). In fact, in stark contrast to the DRC model, the triangle model does not assume that lexical information is represented in the lexicon, but instead assumes that such information is contained in the connections that mediate between the orthographic input and phonological output. Such connection between the orthography and phonology, allows individuals to read both real words and non-words however, additional support from semantics is necessary to support reading of irregular, low frequency words (Plaut et al., 1996). In this vein, the triangle model postulates that, when reading, each of the primary systems of vision (O), phonology (P), and semantics (S) makes distinct contributions that are supported by the division of labour between two pathways.

Thus, in this model, reading can be accomplished by a direct mapping between vision and phonology (O → P) or through the additional support of the semantic system (P ⟷ S) (Plaut et al., 1996). As already mentioned, the direct pathway is implemented to read high-frequency irregular words (e.g., *have*), regular words with consistent spelling-to-sound correspondences (e.g., *mint*) and nonword letter strings through generalization (e.g., *plur*). Words that are uncommon at the level of both whole and subword correspondences (e.g. pint) are susceptible to error if read via the O→P mapping and therefore require additional support from the semantic system (Patterson & Lambon Ralph, 1999). Such support is required to read irregular or exception words (e.g., *pint, colonel*). Therefore, semantics results particularly important in reading aloud those words that have the lowest efficient Orthography -to- Phonology computation (Patterson & Lambon Ralph, 1999). In order to avoid failure in reading when low frequency irregular words are encountered, the support of meaning is necessary. For instance, the word *pint*, which is a low frequency irregular word, would be incorrectly read as rhyming with the regular word *mint* without the additional contribution of semantic information (Hoffman, Lambon Ralph, & Woollams, 2015).

The overall framework is presented below (Figure 1.2).

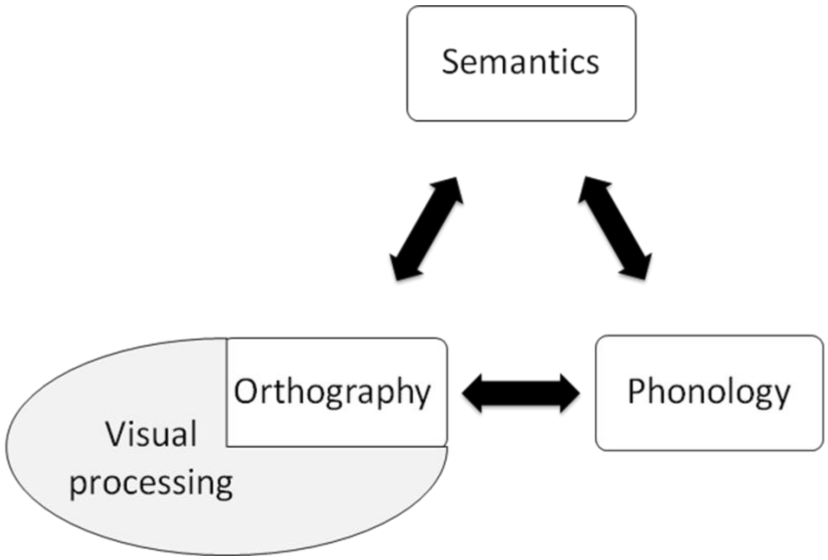

Figure 1.2. The triangle model (Seidenberg & McClleland, 1989; Plaut et al., 1999; Plaut, 1996; Harm & Seidenberg, 2004).

It is important to note that the systems in the triangle model support non-reading tasks. The visual system, for instance, supports reading and other visual tasks such as face and object recognition (Roberts et al., 2015). Additional support to the primary system hypothesis is offered by evidence that graded specialization of visual cortex according to the properties of the stimulus emerges over the course of learning (Behrmann & Plaut, 2015). Specifically, the left hemisphere becomes more finely specialized in word recognition while the right hemisphere becomes more finely tuned for face recognition, however, both hemispheres ultimately participate in both forms of visual recognition (Behrmann & Plaut, 2013a) . Such evidence of graded specialization of the visual cortex contrast with the assumption that specific brain centres are deputed to process specific information (e.g., either faces or words) and is indeed what it would be predicted by the primary system hypothesis (Woollams, 2014a). Similarly, the phonological system will respond to any type of input involving speech production and/or perception (e.g., repetition, rhyme judgment). In this triangle framework, units in the phonological system, are activated in tasks that require speech output (Patterson & Lambon Ralph, 1999). Finally, the semantic system is related to both verbal and non-verbal knowledge, which is developed via detection of higher level correlations between the features of concepts across different modalities (McClelland & Rogers, 2004; Woollams, 2014b).

The more convincing evidence of the characteristics of domain generality - represented by the triangle model- as opposed to the characteristics of domain specificity -represented by the DRC model- come from the neuropsychological patients' data (Hoffman et al., 2015; Woollams, 2014a) and will be discussed in the next section.

To summarise, the development and testing of computational models has had a considerable impact on our understanding of skilled reading. Furthermore, they have been widely employed to simulate typical reading and have been able to account for subtypes of acquired reading impairments (i.e., acquired dyslexia).

1.4 Acquired reading impairments

As discussed in the previous section, computational models, have been employed primarily to describe acquired reading disorders (i.e., acquired dyslexias) in adult skilled readers, that is, in individuals that have lost the capacity to read fluently (Coltheart, 2007; Plaut, 1999).

Acquired disorders of reading can take two forms – peripheral and central. Peripheral dyslexias are neglect, attention dyslexia and pure alexia. These tend to be characterised by a deficit in the visual aspect of the stimuli (before pre-lexical/cognitive components of reading – Riddoch, 1990; Warrington & Shallice, 1980). Central dyslexias are deep, phonological and surface dyslexia, which are caused by impairment to the reading components of the models themselves (Shallice & Warrington, 1980). However, for the purpose of this thesis the focus of the discussion will be on phonological and surface dyslexia profiles.

According to the DRC model, a disruption of one of the two routes might lead to diverse reading difficulties. For instance, a dysfunctional GPC route seems to lead to impaired reading of unfamiliar words, namely phonological dyslexia (Coltheart, 2007).

Phonological dyslexia was first described by Dérouesné (Beauvois & Derouesne, 1979), who observed that these patients presented with "disturbance" in phonological reading, whereas non-phonological reading appeared to be spared (Beauvois & Derouesne, 1979; Derouesné & Beauvois, 1985). Patients with phonological dyslexia present with impairment in reading aloud novel letter strings (e.g., nonwords) whereas their reading of familiar words appears to be spared.

Being unable to employ GPC when they encounter unfamiliar words, phonological dyslexics make lexicalisation errors (e.g., the nonword *ploor* read as the real word *floor*) and also show evidence of the lexicality effect (i.e., words read better than nonwords – e.g., Derouesne & Beauvois, 1979). Both the lexicality effect and lexicalization errors support the hypothesis of dissociation between an impaired nonword reading and a relatively spared familiar word reading procedure. Such evidence is also consistent with the modular approach of the DRC model and the contention that two separate and semi-independent routes underpin reading aloud (e.g., Coltheart et al., 2001).

An opposite pattern of reading impairments characterises patients with a disrupted lexical route in the DRC model, namely surface dyslexics. The term surface dyslexia was used for the first time by Marshall and Newcombe (1973) referring to a patient who could only read by phonologically decoding words. In fact, his capacity to holistically recognise words was compromised and he needed to sound them out to obtain their pronunciation and meaning. Moreover, he particularly struggled to read irregular words (i.e., those words with an irregular letter-to-sound correspondence such as *yacht*) and homophonic words such as “sale” and “sail”. Following the studies of Marshall and Newcombe, a series of cases of surface dyslexia has been described (see Patterson, Marshall, & Coltheart, 2017 for a review).

Being only able to access the GPC route, patients with surface dyslexia usually make regularisation errors (e.g., *pint* read like the regular word *mint*), whereas they may correctly read aloud regular words (e.g., *mint*) and nonwords (e.g., *cind*) (e.g., Marshall & Newcombe, 1973). As previously noted, surface dyslexia occurs due to a deficit in the lexical route of the DRC model (Coltheart, 2007; Coltheart, Masterson, Byng, Prior, & Riddoch, 1983).

Using the lexical route, the word is recognised in the orthographic lexicon and then the corresponding pronunciation is retrieved from the phonological output lexicon. Thus, impairment of one or more components may be responsible for surface dyslexia and force patients to an abnormal reliance on the sub-lexical route (Patterson et al., 2017).

Finally, a particular case of acquired dyslexia is pure alexia, a disorder characterised by slow and inefficient processing of letter strings in the context of intact writing and spelling which was reported for the first time by Déjerine (1892). A predominant characteristic of this reading disorder is the word-length effect (WLE), an increment in word naming latencies as the number of letters in the string increases (e.g., Behrmann & Shallice, 1995). Patients with pure alexia are no longer able to recognise rapidly the whole word and therefore employ a serial letter-by-letter strategy to read. As the sub-lexical route processes letter strings in a left-to-right serial fashion, an overreliance on this route and a consequent damage to the lexical route might account for the reading impairment in pure alexia and for the presence of a WLE. On the other hand, the lexical damage hypothesis fails to explain the pattern of impairments shown by patients with pure alexia. Indeed, reading on the basis of the sub-lexical route, would produce regularisation of irregular words (e.g., *pint* read like *mint*). However, patients with pure alexia do not make regularisation errors (e.g., Cumming, Patterson, Verfaellie, & Graham, 2006). They do though often make letter misidentifications that cannot be supported by an overreliance on the sub-lexical route (Behrmann & Shallice, 1995). Finally, patients with pure alexia are affected by the frequency and imageability of the word, which seems to indicate that the lexical route may be intact (Behrmann, Nelson, & Sekuler, 1998). In this account, pure alexia may arise as damage to the pre-lexical system of the DRC, and, in particular in the letter unit system, in which the visual features of the letters are stored.

Intriguingly, recent investigations have suggested that patients with pure alexia present with impaired visual processing of complex stimuli (e.g., Roberts et al., 2013), that cannot be supported by the DRC model.

The DRC model aligns with the notion of domain specificity in neuropsychology; in this scenario acquired reading disorders result from a deficit to the cognitive components of written language, leaving other systems unaffected.

Such evidence of non-reading visual deficits in pure alexia thus raised the interesting possibility that reading disorders might be better accommodated within a domain general model, in which reading deficits arise from more general non-reading impairments.

An alternative contribution to the study of acquired dyslexias was provided by the primary systems hypothesis and the triangle model. To recap, the triangle model is a domain general computational model which encompasses three primary systems: vision, phonology and semantics. The disruption of any of these systems could result in a distinctly different deficit in reading, along with an impairment in non-reading related tasks. Therefore, disruption to the component deputed to visual processing in the model would result in the visual deficit presented by patients with pure alexia. Moreover, since letters and words are just a particular class of visual objects, a deficit of the visual system may therefore account for reading impairments shown by pure alexics (Roberts et al., 2015, 2013), hence contrasting the attribution of this disorder to a reading-specific deficit. A study conducted by Roberts and collaborators (2013) on patients with pure alexia, provided evidence of a general visual impairment in pure alexics (Roberts et al., 2013). In this case series study, Roberts compared the performance of 20 individuals with pure alexia in reading aloud word of different lengths and non-reading tasks to test the prediction that deficits in pure alexia extend to a general processing of non-orthographic visual stimuli that share some common features with word (high spatial frequency information). They therefore employ two visual matching tasks and employ visual stimuli, namely Kanji characters and Checkerboards, which differed for the level of complexity and similarity with the distractors. The authors found that patients with pure alexia not only struggled to read aloud longer words (i.e., WLE) but their visual deficit affected their performance in the visual tasks and was most apparent in those cases where the stimuli were complex and the distractors were similar. Intriguingly, the performance of patients with pure alexia on these tasks was quantitatively related to the extent of the reading deficit. Such evidence of a deficit in visually processing reading and non-reading stimuli speaks in favour of the primary systems hypothesis and the triangle model (Roberts et al., 2013; Woollams, 2014a).

Phonological dyslexia, on the other hand, might be accounted for by impaired phonological processing caused by a disruption of the phonological component of the triangle model. Indeed, patients with phonological dyslexia, the main characteristic of which is impaired unfamiliar word reading due to a disruption of the phonological route in the DRC model, have been shown to present with a deficit in tasks not directly associated with written words (Woollams & Patterson, 2012). For instance, it has been shown that phonological dyslexia is associated to more general deficit in processing phonological representation which in turn affect nonword reading (Farah, 1996). For instance, evidence that phonological dyslexia may be associated to non-fluent aphasia (i.e., difficulties in language production with relatively spared comprehension Hickok, 1998) following a damage to the perisylvian cortex align with the predictions of general more than specific and restricted to reading impairments in patients with phonological dyslexia (Woollams, 2014b). These findings differ from those attributing phonological dyslexia to a selective reading-specific deficit in grapheme - phoneme mapping and are consistent with the primary systems view, which attributes phonological dyslexia to more general phonological impairments (Woollams, 2014a).

Finally, evidence for an impairment of the semantic component of the triangle model is provided by patients with surface dyslexia, the main characteristic of which is impaired irregular word reading, arising from disruption of the lexical route in the DRC model. Studies have offered evidence of a semantic deficit in individuals with surface dyslexia (see e.g., Woollams, Ralph, Plaut, & Patterson, 2007). Since meaning is required to support the reading aloud of words with inconsistent grapheme-phoneme mappings, such evidence, semantic deficit in surface dyslexia would support the claim that general, non-reading related deficits would cause poor reading in surface dyslexia. Despite some research pointed out that surface dyslexia may present without semantic impairments (Blazely, Coltheart, & Casey, 2005), further evidence has demonstrated the co-existence of damage in the semantic system and surface dyslexia, confirming the prediction of the primary systems hypothesis (Wilson et al., 2009; Woollams et al., 2007; see also Woollams, 2014b).

Taken together these findings suggest that more general non-reading related deficits affect individuals with acquired dyslexia, thereby supporting the primary systems hypothesis. (Woollams, 2014a).

The reading disorders described thus far arise in the context of the normal adult reading system. However, some researchers have been prompted to examine what relationship (if any) might exist between these disorders and developmental dyslexia (Castles & Coltheart, 1993a). On this basis, the computational models described previously have been employed in the area of developmental dyslexia, with the aim of understanding whether patterns of reading could be found in developmental dyslexia which are analogous to those found in acquired dyslexia. These aspects will be discussed in the next section.

1.5 Impaired Reading Development

1.5.1 Developmental Dyslexia

Developmental dyslexia (DD) is a specific learning disorder "*characterised by problems with accurate or fluent word recognition, poor decoding, and poor spelling abilities*"(American Psychiatric Association., 2013 pp. 66,67), These problems "*are substantially and quantifiably below those expected for the individual's chronological age, and cause significant interference with academic or occupational performance, or with activities of daily living*." (American Psychiatric Association, 2013 pp. 66,67).

The neurobiological investigation of reading started more than a century ago when Dejerine (1891) proposed that a portion of the left posterior brain region was critical for reading. Subsequently, research on both acquired and developmental reading disorders has confirmed which neuroanatomic regions are involved in reading. These regions are predominantly focused in the parieto-temporal area (such as the angular gyrus, supramarginal gyrus and posterior portion of the superior temporal gyrus e.g., Damasio & Damasio, 1983; Paulesu, 2001). These areas are related to phonological processing and, indeed, most of the research on DD has been focused on the phonological aspects that seem to be impaired in DD (Carroll & Snowling, 2004; Snowling & Hulme, 1989; Vellutino, 2004).

As explained previously, phonology appears to be of critical importance in reading acquisition, with deficits in phonology underpinning impaired reading acquisition. The role of phonology in reading acquisition and DD led some authors to put forward the influential phonological deficit hypothesis (see Elliot & Grigorenko, 2014 for a review; Snowling, 1995; Stanovich, 1988; Stanovich & Siegel, 1994).

According to this hypothesis, DD is characterised by marked weaknesses in phonological processing as evidenced in phonological awareness, verbal short-term memory and verbal processing speed. Among these components, phonological awareness – the capacity to manipulate the sounds of the spoken language – seems to play a key role in reading acquisition with a sub-component of phonological awareness, phonemic awareness deemed particularly important (Caravolas et al., 2005; Snowling, 1981; Ziegler & Goswami, 2005). Phonemic awareness is the ability to segment spoken words into its phonemic elements and appears to be a particularly critical factor in reading development. Over time, children become able to segment (bug -> b/u/g), blend (b/u/g/ -> bug) and recognize phonemes, that is, the smallest units of the spoken language. If phonemic awareness is poor, children are likely to struggle to acquire the ability to discover spelling to sound relationships and, as a consequence, fail to develop alphabetic coding skills (Elliot & Grigorenko, 2014).

It is proposed that a deficit in phoneme awareness leads children with DD to struggle to develop related phonological skills, such as phoneme-grapheme decoding, which in turn leads to inability to build up an orthographic representation of the word, eventually resulting in poor reading fluency (Richlan, 2014).

Even though the role of impaired phonological processing in DD is now well established, it remains controversial. Some authors, for instance, argued that deficit in the phonological processing are secondary to more basic auditory deficit (see Elliot & Grigorenko, 2014 for a review; see also Ramus et al., 2003). The hypothesis that auditory deficit would affect individuals with DD was supported by evidence that dyslexics show poor performance on a number of auditory tasks, including processing of short sounds (Tallal, 1980). On the basis of earlier work showing that individuals with specific language impairment experienced greater difficulty in tasks of auditory sensitivity, Tallal (1980) examined whether these problems might also be a feature of those with reading disability. This proved to be case, with a positive correlation being found between auditory processing and reading. Tallal concluded that difficulties centred on the perception of rapid tones may cause the development of inadequate phonological skills, which in turn would affect fluent reading achievement (Tallal, 1980).

The hypothesis that an underlying auditory disorder can cause impaired phonological processing did not receive particular claim with some authors demonstrating that a phonological deficit is sufficient to cause poor reading in DD and that auditory disorders, if present, may aggravate phonological processing but not cause it (Ramus et al., 2003). Notwithstanding the criticisms raised regarding impaired auditory processing in DD, this aspect will be investigated in this thesis. Specifically, with the view to evaluate whether auditory deficit would account for poor reading in DD or whether phonological processing would cause reading impairments in DD independently from low-level auditory deficits as suggested by the supporters of the phonological deficit hypothesis (See Study 2, Chapter 3).

Other research attempted to contrast the view that the phonological deficit hypothesis *per se* would account for poor reading in DD. Some authors propose the hypothesis that DD may be caused by impaired visual processing that would affect fluent word reading (Sigurdardottir, Fridriksdottir, Gudjonsdottir, & Kristjánsson, 2018; Stein & Walsh, 1997; Valdois et al., 2003). The strongest support for the contention of a visual processing deficit in DD derived from the magnocellular deficit hypothesis - which suggests that reading difficulties in DD derive from damage to the magnocellular visual system - and from the visual attention span deficit hypothesis - which postulates that reading impairments in DD are caused by a restricted visual attention span (Bosse, Tainturier, & Valdois, 2007a; Stein & Fowler, 1981; Stein & Talcott, 1999; Zoubrinetzky, Bielle, & Valdois, 2014). Both of these however, presented with some limitations and therefore did not seem to be valid alternatives to the acclaimed phonological deficit hypothesis in accounting for reading impairments in DD (Elliot & Grigorenko, 2014).

Other evidence of visual processing deficits in DD has been provided by studies showing impaired face and object recognition (see e.g., Sigurdardottir, Ívarsson, Kristinsdóttir, & Kristjánsson, 2015). However, clear support for the contention of impaired visual processing deficit in DD is still under debate and therefore needs to be further investigated. Given the relevance of the topic for the purpose of this thesis, visual processing deficit will be discussed more in depth later in the chapter.

To investigate patterns of reading difficulties in DD, the same computational models employed to accommodate acquired reading disorders have been used (Coltheart, 1981; Coltheart & Leahy, 1996; Job, Sartori, Masterson, & Coltheart, 1984a). The DRC model, in particular, is the model most widely employed in the literature on DD (Castles & Coltheart, 1993b; Coltheart et al., 2001). To reiterate, in this model, reading is assumed to involve two major processes, or “routes”. First, one can access stored word pronunciations in the phonological lexicon following activation from the orthographic lexicon or semantic system. This lexical process is necessary when reading words with ambiguous or irregular spellings such as *colonel*. Second, reading can occur via a sub-lexical grapheme-to-phoneme conversion process. In contrast to the lexical process, the sub-lexical process can generate plausible pronunciations for regular words or phonologically plausible nonwords but will produce regularisation errors for irregular words (e.g., colonel -> “colernel”; yacht -> “yatched”; sugar -> “sudger”).

Although several subtypes of DD have been described (Castles, Bates, & Coltheart, 2006; Castles & Coltheart, 1993; Friedmann & Coltheart, 2016) there are two strands of evidence that point to some degree of independence between lexical and sub-lexical routes (Castles et al., 2006). First, developmental surface dyslexia is characterised by a difficulty in reading irregular words due to a deficit in the lexical route (Castles, 1996; Job, Sartori, Masterson, & Coltheart, 1984; Zoccolotti et al., 1999). Second, phonological dyslexia is characterised by a difficulty in reading unfamiliar words or nonwords due to a deficit in the phonological or sub-lexical route (Rack, Snowling, & Olson, 1992; Snowling, 1981; Snowling & Hulme, 1989; Temple & Marshall, 1983b). The two sub-groups of DD accounted for by the DRC model will be reviewed in the next section.

1.5.2 Surface developmental dyslexia

A first case of a developmental form of surface dyslexia was described by Holmes (1973) and later by Coltheart, Masterson, Byng, Prior, and Riddoch (1983), and Job, Sartori, Masterson, and Coltheart (1984a). Although this approach to the investigation of DD has been challenged by some authors - whose main argument was the model was primarily developed to explain impaired reading by neurological patients due to brain damage (see e.g., Frith, 1985) - the most prevalent theoretical explanation of developmental reading disorders has been expressed in terms of the DRC model of reading (Coltheart et al., 2001). As has been described in previous sections, in the DRC model there are two ways in which a word might be read aloud: via lexical recognition or via an abstract set of grapheme-phoneme rules. In surface dyslexia, a dysfunctional lexical system leads to a consequent overreliance on the GPC route (i.e., sub-lexical route). For this reason, people with surface dyslexia struggle to read words with an inconsistent spelling to sound correspondence, irregular words, hence being reliant on applying the GPC strategy. The employment of the sub-lexical route to read inconsistent word leads to regularisation errors, that is words with atypical speech-sound correspondence (e.g., *pint*) are read as regular words (e.g., *mint*) (Coltheart, 1981). Despite a compromised capacity to read irregular words, individuals with developmental surface dyslexia show a somewhat intact ability to read aloud regular words and novel strings of letters that have a consistent letter-sound correspondence (Castles, 1996b; Job, Sartori, Masterson, & Coltheart, 1984b; Marshall, 1984; Zoccolotti et al., 1999b).

1.5.3 Phonological dyslexia

Developmental phonological dyslexia is primarily described as a difficulty in reading aloud nonwords (pronounceable letter strings that are not real words e.g., *thag*), whereas reading of familiar words is preserved. It was first described by Temple and Marshall (1983a), who reported the case of a young girl who presented with a discrepant pattern of reading. In particular, she could read aloud familiar regular and irregular words quite well but performed very poorly on nonwords and unfamiliar words. Often, her responses to the nonwords contained word components, suggesting that she used real word analogies in attempting to pronounce the items. On the basis of these symptoms, the authors concluded that this participant had a specific difficulty in using the sub-lexical procedure and that her condition was therefore analogous to acquired phonological dyslexia.

According to the DRC model of reading aloud (Coltheart et al., 2001), a dysfunction in the sub-lexical route may compromise the ability to read using grapheme-phoneme conversion, which results in an inability to read nonwords and novel letter strings. People with phonological dyslexia very often present with lexicalisation (i.e., reading nonwords as if they were real words) and are also affected by the effect of lexicality (i.e., they make fewer errors when they read real words compared to nonword or novel words).

Despite a compromised capacity to read aloud novel letter strings, individuals with phonological dyslexia may correctly read very familiar words, which are stored in their orthographic lexicon and are therefore available to be retrieved during reading (Temple & Marshall, 1983b; Wydell & Butterworth, 1999a). Notably however, the vocabulary of such individuals is poorer compared to that of typical readers. Despite this, they sometimes tend to make lexical substitutions whilst reading (e.g., girl -> grill) (Snowling, 1995; Temple & Marshall, 1983a). Interestingly, these substitutions may happen even when they read regular words, confirming that a faulty sub-lexical route prevents them from segmenting the unfamiliar words and reading through a GPC strategy (Temple & Marshall, 1983b; Wydell & Butterworth, 1999a). Wydell and Butterworth for instance, argued that their case study, AS – an English-Japanese bilingual guy who presented with phonological dyslexia but only in English – was unable to segment letter strings for appropriate phonemes, therefore he tended to use orthographic/visual approximations (he could not segment “girls” so he chose the orthographically/visually closest word Wydell & Butterworth, 1999a)

1.6 Visual processing deficit in developmental dyslexia

Given that reading requires one to visually recognise letter strings, it is unsurprising that a deficit in visual processing has been hypothesised as a factor underlying DD (Orton, 1925). However, the role of visual factors in DD was criticised by Vellutino (2004) who ruled out the hypothesis that visual deficits could play a casual role in reading disorders and rather supported evidence of phonological skills deficiencies as the most plausible causes of DD (Vellutino, 2004). Despite the criticisms raised by researchers (see e.g., Ramus, 2003b) about impaired visual processing in DD, a renewed interest has been expressed in the potential role played by visual processing deficits in reading disability (Elliot & Grigorenko, 2014; Gori, Seitz, Ronconi, Franceschini, & Facoetti, 2016; Lobier, Zoubrinetzky, & Valdois, 2012).

It has been pointed out that not all individuals with reading disabilities exhibit a phonological deficit (e.g., Castles, 1996; Elliot & Grigorenko, 2014) and that individuals with poor phonological abilities can nevertheless develop good reading skills (Howard, 1996). Thus, a single phonological deficit seems not to be the unique cause of poor reading in DD (Bosse, Tainturier, & Valdois, 2007b; Elliot & Grigorenko, 2014; Gibbs & Ellitt, 2020; Giofrè, Toffalini, et al., 2019). The emphasis upon phonological deficit as the exclusive cause of dyslexia may therefore be misleading and result in overlooking a poor readers who do not manifest phonological impairments and may need special assistance in school. There is in fact a proportion of individuals with DD who have been shown to present with problematic visual processing (Valdois et al., 2003; Valdois, Bosse, & Tainturier, 2004) .

It is therefore conceivable to hypothesise that a deficit in the phonological domain might be one of multiple deficits that are likely to interact to cause reading disability, with some authors giving greater weight to the role of visual factors (Bosse et al., 2007b; Vidyasagar & Pammer, 2010a).

A number of different forms of visual processing deficit in reading disability have been proposed. One of the most strongly advocated theoretical explanations of reading deficits in DD suggested that reading disability might be caused by a visual processing deficit in the magnocellular visual system (Livingstone, Rosen, Drislane, & Galaburda, 1991; Stein, 2018a; Stein & Fowler, 1981).

The magnocellular visual system is deputed to process contrast, motion, and rapid changes in the visual field. A reduced sensitivity in the magnocellular system is proposed to cause difficulties in suppressing visual information, which in turn causes an excess of visual information and a reduced visual acuity that affects reading (see Livingstone et al., 1991; see also Valdois et al., 2004 for a review). The magnocellular visual pathway comprises large cells that are responsible for detecting contrast, motion, and rapid changes in the visual field and culminates in the posterior parietal cortex, which plays an important role in guiding visual attention. A disruption in the magnocellular pathway is therefore proposed to lead to deficient visual processing in DD and, via the posterior parietal cortex, to abnormal binocular control and visuospatial attention (see Ramus, 2003b; Stein & Walsh, 1997; Vidyasagar & Pammer, 2010b). Individuals with DD with an underlying deficit of the magnocellular system therefore, would present with an asymmetrical distribution of spatial attention in the two visual fields, being unable to inhibit information from the right visual field and focus attention in the centre of their gaze (Boden & Giaschi, 2007; Facoetti et al., 2006). It has been suggested that individuals with developmental dyslexia present with a deficit in processing stimuli when they are presented very rapidly. Such stimuli are processed via the magnocellular cells in the dorsal pathway. As a consequence, it has been put forward that deficit in the magnocellular pathway may account for poorer performance on a range of visual tasks, and indeed supportive evidence has been provided to support the link between reading difficulties in DD and deficit in this area (see Elliot & Grigorenko, 2014 for a review)

Further to the study of Stein and Walsh, investigation of the magnocellular hypothesis as responsible for the visual processing deficit in DD has been carried out (Facoetti et al., 2006; Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012; Ramus, 2001; Ramus et al., 2003; Stein, 2018a), yet the findings have proven to be inconclusive and somewhat confusing (see Elliot & Grigorenko, 2014; Ramus et al., 2003 for details). Some authors for instance argued that, even though DD presented with visual deficit, this deficit cannot be restricted to the magnocellular pathway (Vidyasagar & Pammer, 2010a). Another source of controversy has been noted as there is actually no clear evidence that a deficit in the magnocellular pathway can contribute to the reading difficulties in DD, independently of phonological impairments (Bosse et al., 2007b; Ramus, 2003a; Valdois et al., 2003).

Consequently, even though the magnocellular deficit hypothesis received great attention in the field of DD, clear evidence of magnocellular deficit in DD has yet to be clearly demonstrated. Some authors, for instance reported that a considerable number of individuals with magnocellular deficits were able to develop adequate reading skills, leaving open the question whether a disfunction in the magnocellular system can cause DD (see Elliot & Grigorenko, 2014 for a review).

Furthermore magnocellular deficit has been reported in phonological dyslexia, that is, impairments in reading unfamiliar regular words and nonwords but fails to account for the impairment in surface dyslexia (Facoetti et al., 2006; Ramus, 2003a).

Another explanation of visual processing deficits in DD is given by sluggish attentional shifting (Franceschini et al., 2012; Lallier, Donnadieu, Berger, & Valdois, 2010). According to this hypothesis, some individuals with DD have abnormal attentional blink, that is they struggle to disengage from visual stimuli when they are presented in rapid sequence (see Broadbent & Broadbent, 1987 and Grassi, Crotti, Giofrè, Boedker, & Toffalini, 2020 for more details on attentional blink).

It has been confirmed that attentional blink and reading are related (McLean, Stuart, Visser, & Castles, 2009), with some authors reporting prolonged attentional blink in individuals with DD (Facoetti, Ruffino, Peru, Paganoni, & Chelazzi, 2008; Franceschini et al., 2012; Lallier, Donnadieu, & Valdois, 2010). Further evidence has linked abnormal attentional blink and therefore sluggish attentional shifting to the magnocellular pathway (Facoetti et al., 2008; Franceschini et al., 2012) in terms of sluggish focused spatial, which account for specifically impaired reading skills in individuals with DD (Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005). However, some authors argued that the contribution of the magnocellular system in this phenomenon is not essential (Stuart, Lambeth, Day, Gould, & Castles, 2012).

Despite such evidence of a possible role played by sluggish attentional shifting in reading disorders, discrepancies raised in the investigations of this phenomenon in DD and the role of attentional shifting in DD has been questioned (Badcock, Hogben, & Fletcher, 2008; Elliot & Grigorenko, 2014; McLean, Castles, Coltheart, & Stuart, 2010).

Most recently, an alternative account that tried to explain visual processing deficits in DD, has contributed to the debate providing a more encompassing explanation of the reading impairments in both phonological and surface DD. It is referred to as visual attention span hypothesis (Bosse et al., 2007b). The visual attention span hypothesis posits that difficulties in

DD are a consequence of a deficit in this aspect of visual processing and proposes the existence of a visual system impairment which is critical in DD (Frey & Bosse, 2018; Lobier et al., 2012; Zoubrinetzky, Collet, Serniclaes, Nguyen-Morel, & Valdois, 2016).

The visual attention span hypothesis is grounded in the connectionist multi-trace memory model of polysyllabic word reading (Ans, Carbonnel, & Valdois, 1998) in which reading depends on the employment of two modes – analytic vs global – which differ in the size of visual attention window they involve. In the global mode, the visual attentional window extends to the whole word whereas it narrows down in the analytical mode. As a consequence, the global mode requires a larger visuo-attentional span than the analytical mode. The two reading procedures also differ from the way phonology is retrieved from the orthographic input. In the global mode, the phonological output is generated in one step. In the analytic mode phonological input is generated successively as the attentional window is restricted to smaller units. Therefore, the information about each unit has to be maintained in short-term memory in order to be available at the end of the process (Ginestet, Phénix, Diard, & Valdois, 2019; Lallier & Valdois, 2012). Within the model, familiar words are generally processed as a whole through the global mode, whereas unfamiliar words and pseudowords are processed through the analytic mode. It has been reported that a reduced visuo-attentional window prevents reading in the global mode. A failure in the global mode would therefore explain reading difficulties in the surface dyslexia profile (Bosse et al., 2007b).

Notably the model suggests that a selective visual attentional or phonological deficit might impact on reading acquisition and result in patterns of developmental surface or phonological dyslexia. A deficit in the global mode would cause difficulties in fast word recognition along with regularisation errors showed by surface dyslexia whereas phonological dyslexia might be accounted for by an independent deficit in phonological processing (see Bosse et al., 2007b).

Interestingly, deficit in visual attention span has proven to affect not only the recognition of letter strings but also extends to other kinds of stimuli, such as numbers and symbols (Lobier et al., 2012). Such evidence therefore suggested that visual attention span deficit is a consequence of impaired visual processing rather than an orthography-to-phonology mapping deficit.

Although the visual attention span hypothesis results in one of the most important theories supporting visual processing deficit in DD, it has been questioned by researchers who argued that it cannot predict deficit in the perception of non-alphanumeric stimuli in DD (Ziegler, Pech-Georgel, Dufau, & Grainger, 2009). Such evidence is in contrast to previous findings of similar impaired visual attention span for letters, numbers and symbols in DD (Lobier et al., 2012) and seems to indicate phonological processing rather than visual attention processing is impaired in DD (Ziegler et al., 2009). To complicate matters further, another study which investigated visual attention span in children with and without DD did not find any group difference in visual attention processing, hence concluding that children with DD did not manifest visual attention span deficits (Banfi et al., 2018). Therefore, although the visual attention span attempted to propose an alternative to the phonological deficit hypothesis in DD, the contention that visual attention span is impaired in dyslexia is still under debate and clear evidence still need to be provided.

Another piece of evidence of impairments in visual processing in DD has been put forward by authors who have suggested that individuals with DD struggle to process more generic complex visual stimuli such as faces, objects and abstract visual patterns (Gabay, Dundas, Plaut, & Behrmann, 2017a; Sigurdardottir et al., 2018). Such a deficit in visual processing seems to be due to a dysfunction in the left posterior ventral occipitotemporal cortex, and in particular impairment of an area generally known as the visual word form area (VWFA see Dehaene & Cohen, 2011a).

The role of the ventral cortex and in particular of the VWFA in reading is well-established (Centanni et al., 2019; Cohen & Dehaene, 2004; Dehaene & Cohen, 2011b; Schurz et al., 2010). The VWFA is proposed to operate on the whole word (word form) recognition (Pugh, 2006; Pugh et al., 2000) and it is this occipitotemporal system that appears to predominate when a reader has acquired mastery and has bound together as a unit the orthographic, phonological, and semantic features of the word (Price & Devlin, 2011b; Pugh, 2006; Pugh et al., 2000; although see Richlan, 2012). Thus, the VWFA plays an important role in fast word recognition in reading, although it has been suggested a contribution of this system to sub-lexical decoding (Cohen & Dehaene, 2004; Dehaene & Cohen, 2011; Price & Devlin, 2011b; Richlan, 2012).

Research on pure alexic patients suggests that lesions to the VWFA not only limit reading but also implicate visual processing in non-reading based tasks (Roberts et al., 2013). These patients often present with deficits in processing visually demanding stimuli such as faces and objects (Albonico & Barton, 2017; Behrmann & Plaut, 2014; Roberts et al., 2015, 2013). Furthermore, a study conducted employing unfamiliar non-orthographic visual stimuli (i.e., Kanji characters and Checkerboards) showed that patients struggled when processing purely visual materials. Interestingly, they were especially sensitive to visual complexity and similarity when discriminating between novel visual patterns. The authors concluded that such results suggested the patients' non-orthographic recognition impairments have a common underlying mechanism and reflected damage to the left posterior fusiform gyrus or "VWFA" (Roberts et al., 2013).

Remarkably, impairments shown by individuals with DD align with those seen in patients with pure alexia. Indeed, as already noted, some people with developmental reading disorder are often characterised by reading performance evidencing a strong WLE (Martens & de Jong, 2006; Spinelli et al., 2005; Zoccolotti et al., 2005) and, more interestingly, by a deficiency in processing non-reading visual stimuli (Gabay et al., 2017a; Sigurdardottir et al., 2018). Moreover, metanalytic findings on brain abnormalities in individuals with DD showed a series of reading-related underactivation in the brains of DDs, including the VWFA (A. Martin, Kronbichler, & Richlan, 2016; Richlan et al., 2010a).

These findings of underactivation in the VWFA in DD along with the behavioural similarities between people with DD and patients with pure alexia, might suggest that a damage/ underactivation of the VWFA is responsible for reading difficulties and, more importantly, for visual impairments more generally, thus strengthening the contention that visual processing plays a casual role in reading disability (Gabay, Dundas, Plaut, & Behrmann, 2017b; Sigurdardottir et al., 2018, 2015).

The evidence of this dual reading and non-reading impairment in DD would not appear to fit within a reading specific model, such as the DRC and has led some researchers to question whether a domain general model, such as the triangle model, wherein impaired reading may be an emergent effect of damage in one of the three primary systems might account for the impairments in DD (Woollams, 2014a). However promising this rationale may be, evidence of the implementation of the primary systems hypothesis to the field of DD has remained scarce, and further research is much needed.

Another aspect which might be related to the impaired processing of visual information in DD regards the evidence that some individuals with DD have visuo-spatial working memory (VSWM) problems (e.g., Smith-Spark & Fisk, 2007). According to the seminal model of Baddeley and Hitch (1974), working memory encompasses two slave systems deputed to the storage of verbal (the phonological loop) and visuo-spatial (visuo-spatial sketchpad) information. Although there is much consensus for impaired verbal working memory in DD (Ackerman & Dykman, 1993a; Gathercole, Alloway, Willis, & Adams, 2006; Gathercole et al., 2016; Smith-Spark & Fisk, 2007), the relationship between a deficit in the visuo-spatial component of WM and DD has received less attention and the evidence of existing VSWM deficit in DD is still under debate (see Elliot & Grigorenko, 2014 for a review).

In fact, some researchers (e.g., Macaruso, Locke, Smith, & Powers, 1996; Swanson, 1978) have argued that the poorer performance of individuals with DD in VSWM tasks actually reflects an underlying deficit in the phonological component of WM. The impaired performance of poor readers in VSWM tasks might indeed be affected by the extent to which the visual stimuli can be phonologically recoded (Elliot & Grigorenko, 2014; Macaruso et al., 1996; Swanson, 1978). However, recent evidence has revealed that individuals with DD were impaired in VSWM tasks even after controlling for phonological WM (Smith-Spark, Fisk, Fawcett, & Nicolson, 2003). It is therefore possible to speculate that visual processing and VSWM are related in the same way as phonology and verbal memory are, thus raising the interesting possibility that a deficit in visual processing might in turn affect performance in VSWM tasks. However promising, evidence of a compromised VSWM in DD is still scarce and would benefit from further systematic investigation.

To sum up, the findings presented thus far provided little evidence that some individuals with DD do present with impaired visual processing, although such evidence is not well supported and therefore further investigation is needed. The ongoing debate on the presence of visual processing deficit in DD led to the investigation of this aspect in this thesis. The scope here was not to dispute the phonological deficit hypothesis. Rather, it was to demonstrate that a double phonological-visual deficit may cause poor reading in some individuals with DD.

1.7 The impact of orthographic depth in reading and DD

1.7.1 Reading acquisition across orthographies

Taking up the previous point, an interesting line of research comparing DD readers of different orthographic systems raised the possibility that the cognitive (e.g., visual and phonological) and neural correlates of DD might vary across languages with different orthographic depth (i.e., the complexity, consistency or transparency of speech-sound correspondences among orthographies see e.g., Frost, Katz, & Bentin, 1987; Landerl et al., 2019, 2013a; Rau, Moll, Snowling, & Landerl, 2015; Richlan, 2014).

Indeed, notwithstanding the body of evidence suggesting that DD is a unitary disorder, there is an increasing amount of research that shows DD might be characterised by different behavioural and neuroanatomical manifestations across languages with a different orthographic depth. This aspect is of crucial importance for the purpose of this thesis, which aimed to compare the performance of individuals with DD reading in languages with varying orthographic consistency/depth. For this reason, the implications of orthographic consistency in reading acquisition and in DD will be discussed in the next section

As clarified at the beginning of the chapter (see section 1.1), reading is accomplished very early by children, usually before the end of the first school year, albeit with some exceptions. Indeed, there is evidence that reading attainment varies between languages with different degrees of "orthographic depth", that is the difference in consistency between the spoken and the written language (see the orthographic depth hypothesis developed by Frost et al., 1987 for further details). Such different levels of consistency of the mapping between spoken language and written language would in turn likely make reading mastery more laborious in certain languages compared to others (Seymour et al., 2003).

Alphabetic orthographies can be classified, on the basis of their concordance between letters (graphemes) and sounds (phonemes), in shallow (hereafter transparent) or deep (hereafter opaque) orthographies. In a transparent orthography the grapheme-phoneme correspondence is almost unequivocal. By contrast, in more opaque orthographies such correspondence is less consistent. Consequently, it has been shown that, readers of transparent orthographies acquire reading easier and quicker than readers of opaque orthographies. In a study conducted by Seymour and collaborators (2003) among European orthographies differing in orthographic depth, it was shown that children from a majority of countries became fluent and accurate readers at the end of the first year of school (Caravolas & Landerl, 2010; Seymour et al., 2003). Differences were found, however, among those orthographies with a higher degree of depth, such as French, Portuguese and in particular English. Such differences tended to be independent from the age at which children started school, but they were influenced by two factors, the syllabic complexity (i.e., the predominance of Consonant-Vowel syllables with a few initial or final consonant clusters Seymour et al., 2003) and the orthographic depth. According to these factors, English was judged to be the opaquest amongst the orthographies investigated and had the highest syllabic complexity. The researchers found that, at the end of the first year of school, English children were slower and less accurate readers than children reading less opaque, less complex orthographies.

Readers of transparent orthographies, such as German or Italian, can access reading by directly converting each grapheme into the correspondent phoneme, allowing them to accomplish fluent reading earlier compared to readers of opaque orthographies, such as English, in which the inconsistency of their writing system, requires the reader to develop a more complex mental dictionary (internal lexicon). This lexicon allows them to read rapidly with accuracy by retrieving the whole word stored in the lexical representation, and is particularly effective for irregular words.

In this way, accomplishing fluent reading may be more onerous for children reading opaque orthographies - and especially for those reading English - compared to those reading transparent orthographies, and thus necessitating more time to become skilled readers.

Another interesting contribution to the contention of differences across orthographies is presented by Ziegler and Goswami (2005). These authors argued that when a young learner approaches reading, they may encounter three problems: availability, consistency and granularity of the letter-sound mapping.

The availability problem resides in the fact that the smallest phonological units (i.e., the phonemes) are not easily accessible prior to reading. Therefore, connecting orthographic units and phonological units requires further cognitive development. Phonics teaching, which explicitly focuses on the correspondence between graphemes and phonemes helps children overcome such problems and has been shown to improve reading abilities (see Ehri et al., 2001 for a meta-analysis on reading achievement in children).

The consistency problem reflects the fact that some orthographic units may have more than one pronunciation and, vice versa, some orthographic units may have more than one spelling. For example, in English, the grapheme i is pronounced /i/ in the word *mint* but it is pronounced /ai/ in the word *pint*. Lastly, the granularity problem relates to the fact that there are more orthographic units to learn when access to the phonology is based on bigger rather than smaller grain sizes (i.e., syllables or whole words). This entails that learning to read by using larger grain size units, as in opaque orthographies (e.g., English) is more complex and therefore readers of opaque orthographies require more time to master reading (Ziegler & Goswami, 2005).

As a consequence, the authors posited that reading proficiency depends on the resolution of these problems and that the efficiency with which such problems are solved depends on the consistency of the orthographic system. Therefore, reading achievement across languages may vary according to the degree of their orthographic consistency.

Whilst the developmental trajectory, at least in European languages, of the phonological representations seems to be the same across orthographies, what seems to impact reading acquisition are the consistency of the speech-sound mapping and the granularity of the orthographic and phonological representations (i.e., smaller vs larger grain size units). These two aspects appear to be connected and indeed, orthographies which present with a lower consistency between letters and sounds employ larger units in reading because of the scant reliability of the smaller units. This requires the young reader of an inconsistent orthography to take more time to become proficient since they need to develop decoding strategies at more than one grain size to read efficiently (e.g., rhyme analogy strategy see Goswami, 1986). Such evidence accounts for the difference in reading acquisition across languages varying in orthographic depth presented earlier in this section (Seymour et al., 2003).

1.7.2 DD in languages with varying orthographic consistency

Given the impact that orthography has on reading acquisition, one might question whether and to what extent, the difference in orthographic consistency might influence the manifestation of DD. As previously noted, the complexity and depth of the orthographic system may lead to difficulties in accomplishing fluent reading in the young learner. Crucially, orthographic complexity may also be detrimental for dyslexic individuals and influence the behavioural manifestation of DD across different orthographic systems.

Wimmer (1993) for instance, posited that reading deficits in languages with transparent orthographies such as German, are characterised by impaired reading speed, although accuracy might be spared. Similar observations have been made in Italian (Zoccolotti et al., 1999b) a language characterised by relatively high grapheme-to-phoneme regularity.

Research conducted in transparent orthographies has indeed suggested that people with DD tend to present with impaired reading speed and a strong WLE whereas accuracy is relatively preserved (Martens & de Jong, 2006; Spinelli et al., 2005; Zoccolotti, De Luca, Di Filippo, Judica, & Martelli, 2009; Zoccolotti et al., 1999b). This effect was proposed to reflect an over-reliance on the sub-lexical route of the DRC model, although this view has been questioned by some authors (Spinelli et al., 2005).

Reading deficits in more opaque orthographies are accompanied by impaired speed but characterised particularly by deficits in reading accuracy. Such differences led Wimmer to distinguish between "speed dyslexia", in which the prevailing deficit manifests in dysfluent word recognition and is predominant in transparent orthographies, and "decoding dyslexia", in which the deficit is observed primarily in incorrect word decoding, and observed predominantly in opaque orthographies (Landerl, Wimmer, & Frith, 1997; Wimmer, 1993).

Further evidence of different manifestations of DD in languages with different orthographic consistency has been proposed by Wydell and Butterworth (1999a), who reported a case of A.S., an English-Japanese bilingual who struggled in reading English, whereas his reading in Japanese was preserved. Behaviourally, A.S., presented with poor phonological recoding, struggling for instance to read words he had never encountered before. A.S. also seemed unable to read aloud novel letter strings, including both words and nonwords. Intriguingly, the authors described his reading as spontaneous and never laborious. The errors he made more frequently while reading aloud real words were lexical substitutions (i.e., he replaced the words presented with other words he retrieved from his, albeit limited, orthographic lexicon).

The performance of A.S., in reading aloud nonwords (i.e., phonologically plausible letter strings which are not real words) was even poorer. Again, the lexicalization errors (i.e., he read the nonwords as if they were real words) produced by A.S. in this task confirmed his preserved access to the orthographic lexicon, whereas he presented with an impaired grapheme-phoneme recoding strategy. Taken together this evidence led the authors to conclude that A.S., presented with phonological dyslexia, thus being able to read aloud very familiar words but struggling with novel words (Wydell & Butterworth, 1999).

Based on these findings, the authors put forward the hypothesis of granularity and transparency, which postulated that in orthographies with a high degree of grapheme-phoneme consistency (i.e., the transparency dimension) as well as in orthographies with a low degree of grapheme-phoneme consistency, but whose units are coarser than graphemes and syllables (i.e., the granularity dimension), phonological dyslexia is rare. The English orthography is characterised by a low degree of grapheme-phoneme correspondence (i.e., it is an opaque orthography); moreover, it is an alphabetic orthography with the smaller constituents being graphemes. Japanese on the other hand consists of two scripts, syllabic Kana and logographic Kanji. Kana characters have a high degree of transparency, that is a high correspondence between each character and their pronunciation. Kanji characters, conversely, are more opaque than Kana, that is the relationship between the characters and the pronunciation is one-to-many. Nonetheless, these characters cannot be decomposed into smaller components, e.g., syllables. Therefore, according to the hypothesis of transparency and granularity, it is rare that readers of Japanese present with phonological dyslexia. For this reason, A.S. struggled to read in English but was particularly proficient in Japanese (Wydell & Butterworth, 1999a).

Additionally, behavioural and neuroanatomical investigations carried out by Wydell and Kondo (2015) demonstrated that A.S. presented with weak activation of the same anatomical area compared to both English and Japanese controls while reading in both languages, namely the superior temporal cortex. This area has been implicated in sub-lexical decoding (see e.g., Paulesu et al., 2000; Wydell, Vuorinen, Helenius, & Salmelin, 2003). The authors concluded that the behavioural dissociation in reading performance shown by A.S. (i.e., poor reading skills in English vs good reading skills in Japanese) and accounted for by the hypothesis of granularity and transparency (Wydell & Butterworth, 1999) is underpinned by similar neuroanatomical underactivation in the superior temporal cortex, although the extent to which such underactivation impacts reading performance is different in the two orthographies (Wydell & Kondo, 2015).

Further evidence of cross-linguistic differences in DD was provided by studies using rapid automatised naming (RAN) (Norton & Wolf, 2012; Wolf, Pfeil, Lotz, & Biddle, 1994). RAN is a measure of how quickly an individual can name familiar stimuli (e.g., letters, numbers, objects) and it has been shown to be correlated with reading fluency (see Elliot & Grigorenko, 2014; Norton & Wolf, 2012).

The cognitive skills tested by RAN are still unclear. Some researchers contend that RAN is a measure of phonological processing (Hulme & Snowling, 2013; Snowling & Hulme., 1994) . However, Studies indicated that measures of naming speed and phonological processing are modestly correlated; Swanson et al. (2003) reported a correlation of .38 in their meta-analysis of correlational studies of phonological awareness and naming speed.

An intriguing explanation of the relation between RAN and reading has been offered by Stainthorp and collaborators (2010). The authors pointed out that RAN is associated with visual discrimination abilities. As a consequence, poor readers performed worse in RAN tasks because of underlying visual discrimination problems (Stainthorp et al., 2010).

Although RAN seems to "universally" predict poor reading across orthographies regardless of the consistency of the writing system (e.g., Landerl et al., 2013b), it appears to have more importance in transparent than in opaque orthographies (Helland & Morken, 2016; Torppa et al., 2013; Wolf & Bowers, 1999). Such evidence is not surprising given that DD in such orthographies is characterised by slow and laborious reading more so than poor decoding (Landerl et al., 1997). In such orthographies, the high correspondence between letters and sounds allows even individuals with DD to achieve a high accuracy rate. In opaque orthographies however,, where DD is characterised by slow and incorrect reading, individuals with DD might present with a double deficit in both phonology (i.e., phonological awareness) and RAN (Landerl et al., 2013b; Wolf & Bowers, 1999). Such evidence led some authors to suggest that orthographic consistency may therefore have an impact in DD (Landerl et al., 2013a, 1997; Rau et al., 2015), hence giving a justification of further investigation of the role of the orthographic consistency in the manifestation of DD provided in this thesis.

Contrasting with the view of differences in DD, Ziegler and Goswami (2005) argued that individuals with DD in all orthographies present with a common deficit in phonological recoding at small grain sizes (i.e., the acquisition of a grapheme-phoneme procedure). This claim appears in odds with the hypothesis of different subgroups of developmental dyslexia and in particular with the existence of the surface dyslexia subgroup, whose hallmark is impaired whole-word recognition with preserved grapheme-phoneme reading strategy (Coltheart et al., 1983, 2001; Friedmann & Coltheart, 2016; Job et al., 1984a; Zoccolotti et al., 1999b). Ziegler and Goswami reported a study of Stanovich and collaborators which suggested that a surface dyslexia profile would arise from a milder form of phonological deficit accompanied by inadequate reading experience and concluded that phonological rather than orthographic deficits lie beneath DD across languages (Ziegler & Goswami, 2005). Indeed, when DDs are compared to reading level matched controls, no difference in accessing whole-word representations is found. Rather, difficulties at sub-lexical level were found even in languages in which reading decoding should be facilitated by the transparency of the orthographic system (see Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003) (Ziegler & Goswami, 2005).

Similar results were presented by Caravolas et al., (2005), who made a cross-linguistic comparison between children with DD reading in Czech (a transparent orthography) and in English (an opaque orthography) on phonemic awareness. They found that the two DD groups did not significantly differ on phonemic awareness, although both groups performed significantly worse than their matched controls. These findings strengthen the contention that phonological processing plays a similar role in the development of reading skills which is independent of the transparency of the orthography (Caravolas et al., 2005).

1.8 Goal of the thesis and research questions

Taken together, the findings proposed thus far on the causes of DD across different orthographies seem to be ambiguous and inconclusive. In particular, the view that the phonological deficit hypothesis *per se* is sufficient to cause poor reading irrespective of the orthography remains unresolved/inconclusive and continues to give rise to animated debate. In summary, a whole body of evidence supports the need to look more carefully at the visual processing skills of DD.

The hypothesis of visual processing impairments as critical in DD has been put forward, although it has been strongly criticised by proponents of the phonological deficit hypothesis (see Vellutino, 2004 for a review). Nevertheless, it has been shown that some of the visual processing difficulties identified in individuals with DD remain problematic for a reading specific model (e.g., the DRC model) and may be better accounted for within a domain general account of the processes underpinning reading such as the primary systems view in which impairment in one of the primary systems can lead to reading and non-reading related difficulties (see e.g., Behrmann & Plaut, 2014 for impaired faces recognition in pure alexia; see also Roberts et al., 2013 for evidence of impaired object recognition in pure alexia; see Woollams et al., 2007 for evidence of semantic dementia in the contex of surface dyslexia; see Woollams, 2014a for a review on non-reading impairments in acquired dyslexia). Finally, the cross-linguistic comparisons of DD raise the question of whether and to what extent individuals with DD present with similar behavioural deficits or whether these might differ according to the degree of consistency of the orthography in which they read.

The principal goal of this thesis is to examine, more precisely, the nature of the cognitive processes which underpin the reading impairments of individuals with DD. Specifically, the extent to which visual processing may be more or less important depending on factors such as the consistency of the orthography. Four main questions will be addressed:

1. Are reading difficulties in DD similar across different orthographies and caused by impaired visual processing? (Study 1 Chapter 2)
2. Do individuals with DD present with a double visual-phonological processing deficit (Study 2, Chapter 3)?
3. Are such impairments better accommodated within the primary systems hypothesis and triangle model? (Study 2, Chapter 3)
4. Might a visual processing deficit differently impact DD in languages with varying orthographic consistency? (Study 3, Chapter 4)

2. Word length effect in English dyslexic readers

This Chapter has been published as an article in the journal Frontiers in Psychology with the title: "The clock counts – length effect in English dyslexic readers" (Provazza, Giofrè, Adams, & Roberts, 2019).

Word length effect (WLE) is a psycholinguistic phenomenon which has been extensively studied in DD for transparent languages in which the correspondence between the spoken and the written language is regular although it is rarely evaluated in opaque orthographies such as English. For this reason, the goal of the study presented in this chapter is to investigate the WLE in an opaque orthography, English. A sample of highly educated adults with DD was compared to matched controls on two reading tasks. The prediction is that WLE is a characteristic of DD across orthographies varying in orthographic transparency and such an effect may be caused by a deficit in visual processing, as demonstrated in the acquired dyslexic literature.

2.1. Introduction

Developmental dyslexia (DD) is a specific learning disorder characterised by problems with accurate or fluent word recognition, poor letter decoding, and poor spelling abilities, that affects up to 15% of the population worldwide (American Psychiatric Association., 2013). Although most of the research regarding DD has been conducted with children, reading difficulties persist throughout life (Bruck, 1985; Eloranta, Närhi, Eklund, Ahonen, & Aro, 2018; Finucci, Gottfredson, & Childs, 1985; Nergård-Nilssen & Hulme, 2014; Shrewsbury, 2016).

The manifestation of DD differs across orthographies. For instance, in transparent orthographies in which the mapping between letters and sounds is more regular and predictable (e.g., Italian), the consistency of the letter-sound correspondence limits the incidence of letter decoding errors (e.g., *volpe* [fox], read as *folpe*). The main feature of DD in transparent orthographies appears to be slow and effortful word reading, with accuracy being relatively well preserved (de Jong & van der Leij, 2003; Job et al., 1984a; Wimmer, 1993). Conversely, in opaque orthographies with more irregular letter-sound correspondence in which the mapping between letters and sounds is not always consistent and predictable (e.g., English), DD tends to be characterised by slow reading and a dramatic impairment in reading accuracy (Landerl et al., 1997; Spinelli et al., 2005; Wimmer, 1993). These patterns led Wimmer (1993) to propose a distinction between "speed dyslexia", affecting individuals reading transparent orthographies, and "decoding dyslexia", affecting individuals reading opaque orthographies (although see Ziegler et al., 2003 for similarities between accuracy and speed across orthographies).

Differences in the manifestation of DD in opaque and transparent orthographies might reflect variances in how reading is accomplished. Opaque orthographies encourage a whole-word reading procedure, due to orthographic irregularity (Frost et al., 1987; Marinelli, Romani, Burani, McGowan, & Zoccolotti, 2016; see also Ziegler & Goswami, 2005 for a review on differences between languages). Given the inconsistency of the mapping between letters and sounds, DD in opaque orthographies is characterised by a high incidence of errors (Wimmer, 1993). Conversely, transparent orthographies encourage a serial analysis of the word, particularly in the early stages of reading acquisition, due to the almost perfect concordance between the letters (graphemes) and the sounds (phonemes) of the words (Frost et al., 1987; Ziegler & Goswami, 2005). Given this letter-sound consistency, in transparent orthographies DD is mainly characterised by slow, although accurate reading (Coltheart & Leahy, 1996; Martens & de Jong, 2006; Wimmer, 1993; Ziegler & Goswami, 2005; Zoccolotti et al., 1999a). This pattern of difficulties seems to persist in adulthood (Eloranta et al., 2018; Lindgrén & Laine, 2011; Martin et al., 2010; Re, Tressoldi, Cornoldi, & Lucangeli, 2011; Suárez-Coalla & Cuetos, 2015).

A cross-cultural study conducted with English and Italian children to investigate reading acquisition in these orthographies showed that, even in the early stage of reading acquisition, English children were faster than Italian children, although less accurate (Marinelli et al., 2016). Interestingly, a word length effect (WLE) was present in younger children in both groups; however, it disappeared in older English children and persisted only in Italian children. These results suggest that children reading a transparent orthography persisted in adopting a serial strategy, whilst children reading the opaque orthography did not. This pattern is consistent with evidence from adult English readers where exposure to words through reading acquisition decreases the likelihood that a serial, phonological decoding strategy will be employed. Given the characterization of reading impairment in transparent orthographies is captured in reading latency, the WLE in DD has been more extensively evaluated in these orthographies in both adults and children (see Davies, Cuetos, & Glez-Seijas, 2007 for Spanish children; Richlan et al., 2010b for German adults; Suárez-Coalla & Cuetos, 2015 for spanish adults; Zoccolotti et al., 2005 for Italian children), but scarcely investigated in English (see e.g., Kemp, Parrila, & Kirby, 2009; Ziegler et al., 2003).

WLE has been considered as a pathognomonic symptom in acquired disorders of reading such as pure alexia (Behrmann et al., 1998; Behrmann & Shallice, 1995; Montant & Behrmann, 2001; Roberts et al., 2015; Roberts, Lambon Ralph, & Woollams, 2010; Roberts et al., 2013), a disorder caused by damage to the left fusiform gyrus in the ventral occipitotemporal cortex (Behrmann &

Plaut, 2013b; Price & Devlin, 2011a; Roberts et al., 2013). Support for the contention that this area may also be important in DD is provided by Richlan and colleagues (2010b). They found that adult participants with DD presented with abnormalities of the left occipitotemporal cortex, that is hypoactivation of the left occipitotemporal cortex in response to reading tasks. In addition, reading performance of these participants was also captured by strong WLE. It should be acknowledged, however, that this evidence is from readers of a transparent orthography (German). Whether WLE is a core deficit in adult DD participants reading an opaque orthography is yet to be determined.

One cognitive model employed to explain the WLE in reading is the Dual-Route Cascaded (DRC) model (Coltheart et al., 2001). Although the DRC model was initially implemented to explain deficits in acquired dyslexia, it also accommodates deficits in developmental reading disorders and is widely employed in research on DD (Castles, Bates, & Coltheart, 2006; Castles & Coltheart, 1993a; Coltheart, 2015; Coltheart & Leahy, 1996).

In this model, reading can be achieved via two routes: i) lexically through access to stored representations in the orthographic and phonological lexicons, and ii) sub-lexically through a phonological conversion procedure. The lexical route permits reading of familiar words in parallel whilst the sub-lexical route processes unfamiliar words and phonologically plausible nonwords (e.g., plur) through a serial spelling-to-sound (grapheme-to-phoneme) mechanism. In this conceptualisation, the serial processing of graphemes results in a WLE whereas words read via the lexical route, with parallel processing of graphemes, predicts that a WLE will not be observed. The larger the WLE the greater the reliance on the sub-lexical route (Martens & de Jong, 2006). Hence, within the DRC model, the WLE might be considered to reflect an over-reliance on the sub-lexical route (Barca, Burani, Di Filippo, & Zoccolotti, 2006).

An alternative to the DRC account of the underpinnings of reading achievement is the triangle model, which is implemented in a parallel distributed processing (PDP) connectionist network (Plaut et al., 1996). The triangle model has received substantial support in explaining various types of acquired dyslexia (Hoffman et al., 2015; Patterson & Lambon Ralph, 1999). This view differs from the DRC in that reading is underpinned by the phylogenetically more mature primary systems of vision, phonology, and semantics. Central to this approach is the proposal that the same computational elements, in various combinations, support different activities during word reading: (1) vision, which with respect to reading mediates knowledge about orthographic word form; (2) phonology – the internal representation of word sound; and (3) semantics – word meaning. Reading aloud can be accomplished directly between vision and phonology (V>P) or mediated by semantics (V>S or the interplay between S<>P). During reading acquisition, the direct pathway becomes sensitive to the relationship that exists between graphemes and phonemes and achieves efficient computations for regular words and nonwords with typical grapheme-phoneme rules (e.g., *pat*, *snat*). It is less efficient for infrequent irregular words with atypical grapheme-phoneme rules (e.g., *poignant*) and it is these that may require additional semantic support. In the scenario of the triangle model, WLE may be the result of damage to the visual system (e.g., Roberts et al., 2013).

The present study aimed to examine whether WLE are present in DD reading of English orthography. Few studies have investigated WLE in English children with DD (for an exception see Ziegler et al., 2003) and to the best of our knowledge, evidence of WLE in adult English speakers with DD is scarce. It is possible that, even if WLE affect the reading performance of English children with DD, by adulthood they will have acquired adequate strategies to compensate for their deficit. However, it is also possible that the WLE persist in adulthood, suggesting an overreliance on the sub-lexical route to read, in the scenario of the DRC model, or a deficit in the visual system, in the scenario of the triangle model. To evaluate between these possibilities, we compared a group of English university students with a diagnosis of DD, alongside a group of typical developing readers (TDR) in a word reading task. Such a population represents individuals who might have compensated their reading difficulties in some way and achieve well academically (Cavalli, Duncan, Elbro, El Ahmadi, & Colé, 2017; Kemp et al., 2009; Lefly & Pennington, 1991). To do so they may have received extensive instructional support. Evidence from this population of a resistant WLE therefore speaks to a more stringent test of a core deficit in reading processes. Both accuracy and reaction times (RT) have been analysed. Following evidence of increased reliance on the sub-lexical route with decreasing word familiarity (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; Weekes, 1997) both nonword reading and the effect of word frequency were also explored.

2.2. Method

2.2.1. Participants

Eighteen university students with DD (5 males; age range 19-27; M_{years}= 21.8; SD= 2.29) participated. All had normal or corrected-to-normal vision and were in receipt of a formal diagnosis of dyslexia (supplied by a registered assessor of SpLD) as required for access arrangements and additional support in UK higher education institutions. These diagnoses follow DSM-IV recommendations (American Psychiatric Association, 1994) and the guidelines adopted in public services, namely normal level of general intelligence (IQ above 85; although we did not obtain a measure of IQ as part of this study), reading performance at a clinical level, and no neurological, sensory, or educational deficit that could be a cause of their reading impairment.

They have been contrasted to a TDR group of 18 students (7 males; age range 19-28; M_{years}=21.8; SD=2). The two groups did not differ for gender ($\chi^2(1) = 0.50$, $p = .480$, Cramer's $V = .118$) or age ($F(1, 34) = 0.02$, $p = .878$, $\eta^2_p = .001$). The study was reviewed and approved by Liverpool John Moores University Research Committee and by the RES Committee North West Liverpool Central (15/NW/0461). Written consent was obtained from all participants.

2.3.Materials and procedure

2.3.1 Single word reading (Roberts et al., 2010)

In this and all subsequent tasks, stimuli were presented using E-Prime 2.0 software on a PC. Participants were seated approximately 50 cm from the screen. A list of 180 words comprising 60 words of three, five and seven letters were administered. These included 30 low frequency words and 30 high frequency words in each length set, matched for CELEX written word frequency across the three letter lengths (three letters: low 1.08, high 151.96, average 76.52; five letters: low 1.10, high 130.76, average 65.93; seven letters: low 1.9, high 145.19, average 73.57 – for details see Roberts et al., 2010). Significant frequency effects were observed within each length and collapsed across length (ts> 6.8; ps<.001).

Stimuli were randomised and presented in the same order for each participant. Each word was presented after a fixation point with a duration of 500 milliseconds, remaining on screen until the participant responded. Participants were instructed to read the words aloud as fast and accurately as possible. Reading latencies were measured using the E-Prime voice key and calculated from the onset of the stimulus to the onset of the correct naming response and, therefore, encompass the time taken to identify individual letters. Reading accuracy was recorded by the experimenter using a response box. Participant responses were also recorded allowing the accuracy of pronunciation to be reviewed and agreed by two researchers. A number of responses were excluded from the analyses of RT: incorrect responses, responses below 200 milliseconds and those considered invalid due to technical problems (e.g., microphone errors).

2.3.2 Single nonword reading (Roberts et al., 2013)

Monosyllabic nonwords of three, four, five and six letters were used (17 for each length). Nonwords were pronounceable letter strings, derived by changing one letter of a standardised English word list (Weekes, 2007, Roberts et al., 2013) and provided the initial phoneme of that word remained intact. Nonwords were matched for number of phonemes, summed bigram frequency, and average grapheme frequency. The procedure was identical to that described above. It is important to note that the time between the onset of the word or nonword stimulus to the onset of the correct naming response is an index of the LE. Of course, when subjects begin to pronounce the string, they have already decided that reading is lexical or non-lexical.

2.4.Data analytic strategy

Generalised linear mixed-effects model (GLMM), a robust analysis that allows controlling for the variability of items and subjects (Baayen, Tweedie & Schreuder, 2002), was implemented. GLMM limits the loss of information due to the prior averaging of the by-item and by-subject analyses and has been repeatedly used in the case of RT and errors (Marinelli et al., 2016; Paizi, De Luca, Zoccolotti, & Burani, 2013). Analyses were carried out using R (R Core Team, 2019), with the package lme4 for fitting the models (Bates, Mächler, Bolker, & Walker, 2015, 2017), and the package ggplot2 for the graphics (Wickham, 2009). The package lmerTest was used to obtain p-values and summary tables for lmer model fits on RT (Kuznetsova, Brockhoff, & Christensen, 2017), while a traditional model comparison was used for the accuracy. Participants and items were used as independent random effects. Fixed effects varied in different analyses.

As for words, Group (DD vs. TDR), Frequency (High vs. Low), and Length (3, 5, and 7 letters) were used as fixed factors. Concerning nonwords, Group (DD vs. TDR), and Length (3, 4, 5, and 6 letters) were included as fixed factors. Analysis of the RT were repeated using data transformation in z-scores, to control for over-additive effects (see Paizi et al., 2013 for a similar approach). It is worth noting that this transformation fixes the grand average of each participant (and therefore of each group) to zero. Therefore, in all z-score analyses the fixed effect of group and the random effects of subject tend to be closer to zero. Note that the higher the z-score, the lower the performance.

2.5 Results

2.5.1 A priori power analysis

Given the relatively small sample size a power analysis, using G-Power (Erdfelder, Faul, & Buchner, 1996) has been performed prior to data collection to determine the sufficiency of the sample estimating a moderate effect size based on Cohen's (1988) thresholds. Considering an alpha level of .05, and a correlation between measurements of .5 a sample of 10 participants has a power of .80 to detect a significant interaction. Considering within factors effects, a sample size of 8-10 is required to detect significant differences with a power of .80. Finally, concerning the between factor effect, a sample of 28 is needed to have a power of .80 to detect significant effects. The sample size of 36, which was the sample size that we decided to obtain, has a power of .90 to detect a significant effect of the between factor manipulation. The analytic approach that we decided to use (i.e., GLMM), strengthens the experimental power of the by-subject and by-item analyses and limits the loss of information due to the prior averaging of the by-item and by-subject analyses (Baayen et al., 2002; Paizi et al., 2013).

2.5.2 Descriptive statistics

Means and standard deviations for both RT and accuracy of the two groups are displayed in Table 2.1.

Table 2.1 Descriptive statistics for reading speed and accuracy as a function of group

Measure	DD M	DD SD	TDR M	TDR SD	Cohen's *d*
Length RT (ms)					
Word 3 letters	703.96	153.07	553.66	72.59	1.25
Word 5 letters	751.8	209.06	559.71	71.95	1.23
Word 7 letters	846.4	250.41	568.71	66.76	1.51
NW 3 letters	853.86	335.17	587.76	80.79	1.09
NW 4 letters	936.09	355.84	609.59	110.02	1.24
NW 5 letters	1084.44	496.72	620.01	114.88	1.29
NW 6 letters	1176.076	592.01	628.56	116.33	1.28
Length accuracy (%)					
Word 3 letters	95	4	97	2	0.63
Word 5 letters	91	6	95	2	0.89
Word 7 letters	90	8	95	3	0.83
NW 3 letters	87	14	95	4	0.78
NW 4 letters	87	14	95	4	0.78
NW 5 letters	82	18	95	4	1
NW 6 letters	87	13	96	6	0.89
Frequency RT (ms)					
HF 3 letters	665.90	143.22	544.02	75.07	1.06
HF 5 letters	696.04	177.13	552.95	74.84	1.05
HF 7 letters	729.78	206.74	545.23	65.83	1.20
LF 3 letters	744.78	169.93	563.78	74.80	1.38
LF 5 letters	819.58	262.71	567.83	76.67	1.30
LF 7 letters	998.56	358.18	595.54	74.20	
Frequency accuracy (%)					
HF 3 letters	98	1	98	1	0
HF 5 letters	97	3	99	1	0.89
HF 7 letters	98	2	99	1	0.63
LF 3 letters	92	8	96	3	0.66
LF 5 letters	85	9	92	6	0.91
LF 7 letters	83	15	91	7	0.68

Note. TDR = typical developing readers; DD = developmental dyslexics; HF = high frequency; LF = low frequency; NW = nonwords; RT = reaction times in milliseconds (ms).

2.5.3 Word reading

2.5.3.1 *Reaction times*

Results for the GLMM on word RT are displayed in Figure 1. Significant main effects were observed for Group, $F(1, 34) = 17.54$, $p < .001$, Length, $F(2, 168) = 21.98$, $p < .001$, and Frequency, $F(1, 168) = 79.85$, $p < .001$. Significant interactions were observed for Group × Length × Frequency, $F(2, 5877) = 15.83$, $p < .001$, Group × Length, $F(2, 5877) = 56.30$, $p < .001$, Group × Frequency, $F(1, 5877) = 144.50$, $p < .001$, and Length × Frequency, $F(2, 168) = 8.93$, $p < .001$. The results of this word reading task demonstrate that only the DD group was affected by length and this effect was larger for longer unfamiliar words, particularly in the low frequency condition between lengths three and seven ($t = -8.28$, $p < .001$) and lengths five and seven ($t = -7.67$, $p < .001$). No length effects were present in the high frequency condition for the DD group (ps $\geq .908$). The TDR group did not show any length effects (ps $\geq .980$). Post-hoc analyses on the three-way interaction are presented in Table 2.2.

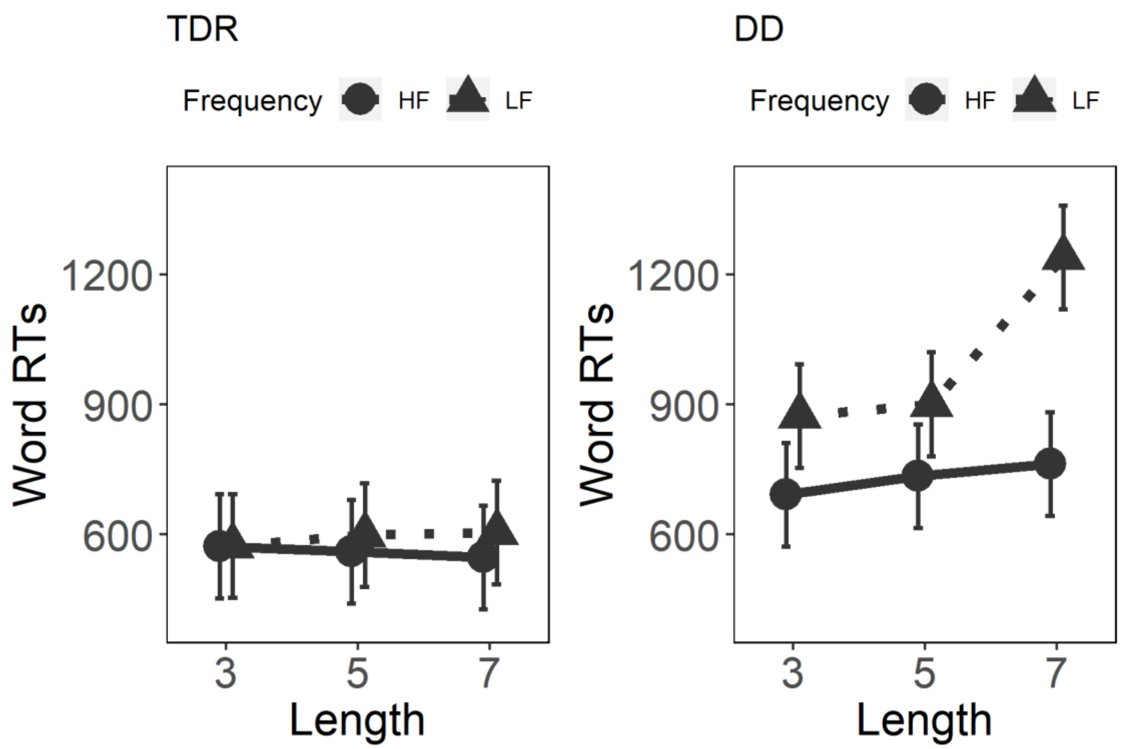

Figure 2.1. *Three-way interaction on the speed on Words. TDR = typical developing readers; DD = developmental dyslexics; HF = high frequency; LF = low frequency; RT = reaction times*

Table 2.2 Word reading post-hoc comparisons on the raw data using Tukey correction

	Contrast	Estimate	SE	t ratio	p value
1	HF,3,TDR - LF,3,TDR	-0.30	44.09	-0.01	1.000
2	HF,3,TDR - HF,5,TDR	13.11	44.09	0.30	1.000
3	HF,3,TDR - LF,5,TDR	-25.38	44.09	-0.58	1.000
4	HF,3,TDR - HF,7,TDR	25.56	44.09	0.58	1.000
5	HF,3,TDR - LF,7,TDR	-31.45	44.09	-0.71	1.000
6	HF,3,TDR - HF,3,DD	-118.68	35.60	-3.33	0.041
7	HF,3,TDR - LF,3,DD	-300.78	44.09	-6.82	0.000
8	HF,3,TDR - HF,5,DD	-162.28	44.09	-3.68	0.014
9	HF,3,TDR - LF,5,DD	-327.70	44.09	-7.43	0.000
10	HF,3,TDR - HF,7,DD	-189.30	44.09	-4.29	0.001
11	HF,3,TDR - LF,7,DD	-666.01	44.09	-15.11	0.000
12	LF,3,TDR - HF,5,TDR	13.40	44.09	0.30	1.000
13	LF,3,TDR - LF,5,TDR	-25.08	44.09	-0.57	1.000
14	LF,3,TDR - HF,7,TDR	25.86	44.09	0.59	1.000
15	LF,3,TDR - LF,7,TDR	-31.16	44.09	-0.71	1.000
16	LF,3,TDR - HF,3,DD	-118.38	44.09	-2.69	0.238
17	LF,3,TDR - LF,3,DD	-300.48	35.60	-8.44	0.000
18	LF,3,TDR - HF,5,DD	-161.98	44.09	-3.67	0.014
19	LF,3,TDR - LF,5,DD	-327.41	44.09	-7.43	0.000
20	LF,3,TDR - HF,7,DD	-189.00	44.09	-4.29	0.001
21	LF,3,TDR - LF,7,DD	-665.72	44.09	-15.10	0.000
22	HF,5,TDR - LF,5,TDR	-38.49	44.09	-0.87	0.999
23	HF,5,TDR - HF,7,TDR	12.45	44.09	0.28	1.000
24	HF,5,TDR - LF,7,TDR	-44.56	44.09	-1.01	0.997
25	HF,5,TDR - HF,3,DD	-131.78	44.09	-2.99	0.116
26	HF,5,TDR - LF,3,DD	-313.89	44.09	-7.12	0.000
27	HF,5,TDR - HF,5,DD	-175.39	35.60	-4.93	0.000
28	HF,5,TDR - LF,5,DD	-340.81	44.09	-7.73	0.000
29	HF,5,TDR - HF,7,DD	-202.41	44.09	-4.59	0.000
30	HF,5,TDR - LF,7,DD	-679.12	44.09	-15.40	0.000
31	LF,5,TDR - HF,7,TDR	50.94	44.09	1.16	0.992
32	LF,5,TDR - LF,7,TDR	-6.07	44.09	-0.14	1.000
33	LF,5,TDR - HF,3,DD	-93.30	44.09	-2.12	0.611
34	LF,5,TDR - LF,3,DD	-275.40	44.09	-6.25	0.000
35	LF,5,TDR - HF,5,DD	-136.90	44.09	-3.11	0.085
36	LF,5,TDR - LF,5,DD	-302.33	35.60	-8.49	0.000
37	LF,5,TDR - HF,7,DD	-163.92	44.09	-3.72	0.012
38	LF,5,TDR - LF,7,DD	-640.64	44.09	-14.53	0.000

39	HF,7,TDR - LF,7,TDR	-57.01	44.09	-1.29	0.980
40	HF,7,TDR - HF,3,DD	-144.24	44.09	-3.27	0.053
41	HF,7,TDR - LF,3,DD	-326.34	44.09	-7.40	0.000
42	HF,7,TDR - HF,5,DD	-187.84	44.09	-4.26	0.002
43	HF,7,TDR - LF,5,DD	-353.26	44.09	-8.01	0.000
44	HF,7,TDR - HF,7,DD	-214.86	35.60	-6.03	0.000
45	HF,7,TDR - LF,7,DD	-691.57	44.09	-15.69	0.000
46	LF,7,TDR - HF,3,DD	-87.22	44.09	-1.98	0.708
47	LF,7,TDR - LF,3,DD	-269.33	44.09	-6.11	0.000
48	LF,7,TDR - HF,5,DD	-130.83	44.09	-2.97	0.122
49	LF,7,TDR - LF,5,DD	-296.25	44.09	-6.72	0.000
50	LF,7,TDR - HF,7,DD	-157.85	44.09	-3.58	0.020
51	LF,7,TDR - LF,7,DD	-634.56	35.60	-17.82	0.000
52	HF,3,DD - LF,3,DD	-182.10	44.09	-4.13	0.003
53	HF,3,DD - HF,5,DD	-43.60	44.09	-0.99	0.998
54	HF,3,DD - LF,5,DD	-209.03	44.09	-4.74	0.000
55	HF,3,DD - HF,7,DD	-70.62	44.09	-1.60	0.908
56	HF,3,DD - LF,7,DD	-547.34	44.09	-12.41	0.000
57	LF,3,DD - HF,5,DD	138.50	44.09	3.14	0.077
58	LF,3,DD - LF,5,DD	-26.92	44.09	-0.61	1.000
59	LF,3,DD - HF,7,DD	111.48	44.09	2.53	0.325
60	LF,3,DD - LF,7,DD	-365.23	44.09	-8.28	0.000
61	HF,5,DD - LF,5,DD	-165.42	44.09	-3.75	0.011
62	HF,5,DD - HF,7,DD	-27.02	44.09	-0.61	1.000
63	HF,5,DD - LF,7,DD	-503.73	44.09	-11.43	0.000
64	LF,5,DD - HF,7,DD	138.41	44.09	3.14	0.077
65	LF,5,DD - LF,7,DD	-338.31	44.09	-7.67	0.000
66	HF,7,DD - LF,7,DD	-476.71	44.09	-10.81	0.000

Note. TDR = typical developing readers; DD = developmental dyslexics; HF = high frequency; LF = low frequency.

2.5.3.2 *Z-scores*

Results for the GLMM on word z-scores are displayed in Figure 2.2. Significant main effects were observed for Length, $F(2, 165) = 14.07$, $p < .001$, and Frequency, $F(1, 165) = 59.37$, $p < .001$, with no effect of Group, $F(1, 5905) = 0.08$, $p = .779$. This latter result is not surprising since all individual performances have been centred to the zero through the z-score transformation. Significant interactions were observed for Group × Length × Frequency, $F(2, 5905) = 5.76$, $p < .001$, Group × Length, $F(2, 5905) = 25.66$, $p < .001$, Group × Frequency, $F(1, 5905) = 49.13$, $p < .001$, and Length × Frequency, $F(2, 165) = 6.38$, $p < .001$. The results obtained with the z-score transformation replicated those obtained with the raw data. Post-hoc analyses on the three-way interaction are presented in Table 2.3.

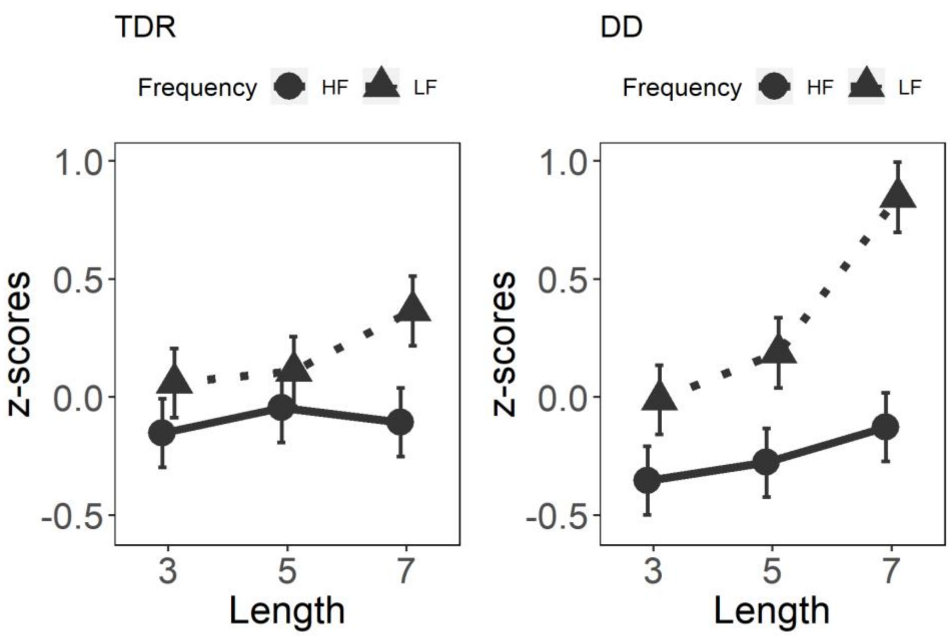

Figure 2.2. Three-way interaction on z-scores on words. Higher z-scores reflect lower performance. TDR = typical developing readers; DD = developmental dyslexics; HF = high frequency; LF = low frequency.

Table 2.3. Word reading post-hoc comparisons on the z-scores using Tukey correction

	Contrast	Estimate	SE	t ratio	p value
1	HF,3,TDR - LF,3,TDR	-0.21	0.11	-1.94	0.736
2	HF,3,TDR - HF,5,TDR	-0.10	0.11	-0.92	0.999
3	HF,3,TDR - LF,5,TDR	-0.27	0.11	-2.53	0.329
4	HF,3,TDR - HF,7,TDR	-0.05	0.11	-0.50	1.000
5	HF,3,TDR - LF,7,TDR	-0.51	0.11	-4.80	0.000
6	HF,3,TDR - HF,3,DD	0.19	0.06	3.44	0.029
7	HF,3,TDR - LF,3,DD	-0.16	0.11	-1.52	0.932
8	HF,3,TDR - HF,5,DD	0.11	0.11	1.01	0.997
9	HF,3,TDR - LF,5,DD	-0.36	0.11	-3.35	0.044
10	HF,3,TDR - HF,7,DD	-0.05	0.11	-0.45	1.000
11	HF,3,TDR - LF,7,DD	-1.01	0.11	-9.33	0.000
12	LF,3,TDR - HF,5,TDR	0.11	0.11	1.01	0.997
13	LF,3,TDR - LF,5,TDR	-0.06	0.11	-0.60	1.000
14	LF,3,TDR - HF,7,TDR	0.15	0.11	1.44	0.955
15	LF,3,TDR - LF,7,TDR	-0.31	0.11	-2.87	0.159
16	LF,3,TDR - HF,3,DD	0.40	0.11	3.71	0.014
17	LF,3,TDR - LF,3,DD	0.04	0.06	0.77	1.000
18	LF,3,TDR - HF,5,DD	0.31	0.11	2.95	0.133
19	LF,3,TDR - LF,5,DD	-0.16	0.11	-1.44	0.955
20	LF,3,TDR - HF,7,DD	0.16	0.11	1.49	0.942
21	LF,3,TDR - LF,7,DD	-0.80	0.11	-7.41	0.000
22	HF,5,TDR - LF,5,TDR	-0.17	0.11	-1.61	0.903
23	HF,5,TDR - HF,7,TDR	0.05	0.11	0.42	1.000
24	HF,5,TDR - LF,7,TDR	-0.42	0.11	-3.88	0.007
25	HF,5,TDR - HF,3,DD	0.29	0.11	2.70	0.231
26	HF,5,TDR - LF,3,DD	-0.06	0.11	-0.61	1.000
27	HF,5,TDR - HF,5,DD	0.21	0.06	3.75	0.010
28	HF,5,TDR - LF,5,DD	-0.26	0.11	-2.44	0.384
29	HF,5,TDR - HF,7,DD	0.05	0.11	0.48	1.000
30	HF,5,TDR - LF,7,DD	-0.91	0.11	-8.43	0.000
31	LF,5,TDR - HF,7,TDR	0.22	0.11	2.03	0.671
32	LF,5,TDR - LF,7,TDR	-0.24	0.11	-2.25	0.515
33	LF,5,TDR - HF,3,DD	0.46	0.11	4.29	0.002
34	LF,5,TDR - LF,3,DD	0.11	0.11	1.00	0.998
35	LF,5,TDR - HF,5,DD	0.38	0.11	3.53	0.025
36	LF,5,TDR - LF,5,DD	-0.09	0.06	-1.56	0.923
37	LF,5,TDR - HF,7,DD	0.22	0.11	2.08	0.635
38	LF,5,TDR - LF,7,DD	-0.74	0.11	-6.77	0.000

39	HF,7,TDR - LF,7,TDR	-0.46	0.11	-4.30	0.001
40	HF,7,TDR - HF,3,DD	0.24	0.11	2.28	0.493
41	HF,7,TDR - LF,3,DD	-0.11	0.11	-1.03	0.997
42	HF,7,TDR - HF,5,DD	0.16	0.11	1.51	0.935
43	HF,7,TDR - LF,5,DD	-0.31	0.11	-2.86	0.164
44	HF,7,TDR - HF,7,DD	0.01	0.06	0.10	1.000
45	HF,7,TDR - LF,7,DD	-0.96	0.11	-8.85	0.000
46	LF,7,TDR - HF,3,DD	0.70	0.11	6.57	0.000
47	LF,7,TDR - LF,3,DD	0.35	0.11	3.26	0.057
48	LF,7,TDR - HF,5,DD	0.62	0.11	5.80	0.000
49	LF,7,TDR - LF,5,DD	0.15	0.11	1.40	0.962
50	LF,7,TDR - HF,7,DD	0.47	0.11	4.35	0.001
51	LF,7,TDR - LF,7,DD	-0.49	0.06	-8.42	0.000
52	HF,3,DD - LF,3,DD	-0.35	0.11	-3.30	0.051
53	HF,3,DD - HF,5,DD	-0.08	0.11	-0.77	1.000
54	HF,3,DD - LF,5,DD	-0.55	0.11	-5.10	0.000
55	HF,3,DD - HF,7,DD	-0.24	0.11	-2.23	0.533
56	HF,3,DD - LF,7,DD	-1.20	0.11	-11.09	0.000
57	LF,3,DD - HF,5,DD	0.27	0.11	2.53	0.326
58	LF,3,DD - LF,5,DD	-0.20	0.11	-1.83	0.801
59	LF,3,DD - HF,7,DD	0.12	0.11	1.08	0.995
60	LF,3,DD - LF,7,DD	-0.85	0.11	-7.78	0.000
61	HF,5,DD - LF,5,DD	-0.47	0.11	-4.34	0.001
62	HF,5,DD - HF,7,DD	-0.16	0.11	-1.46	0.950
63	HF,5,DD - LF,7,DD	-1.12	0.11	-10.33	0.000
64	LF,5,DD - HF,7,DD	0.31	0.11	2.91	0.146
65	LF,5,DD - LF,7,DD	-0.65	0.11	-5.90	0.000
66	HF,7,DD - LF,7,DD	-0.96	0.11	-8.89	0.000

Note. TDR = typical developing readers; DD = developmental dyslexics; HF = high frequency; LF = low frequency.

2.5.3.3 Errors

Results for the GLMM on word errors are displayed in Table 2.1 and Figure 2.3. Significant main effects were observed for Group, $z = -2.73$, $p = .006$, and Frequency, $z = -7.22$, $p < .001$. For Length, only the difference between lengths three and seven was significant, $z = -2.12$, $p <.05$.

These results demonstrate that the DD group performed worse than the TDR group. Additionally, both groups were more accurate in the high frequency condition as shown by the main effect of frequency. Intriguingly, the performance in both groups was very high. Only the longest words (7 letters) were read worse than the other words in the DD group.

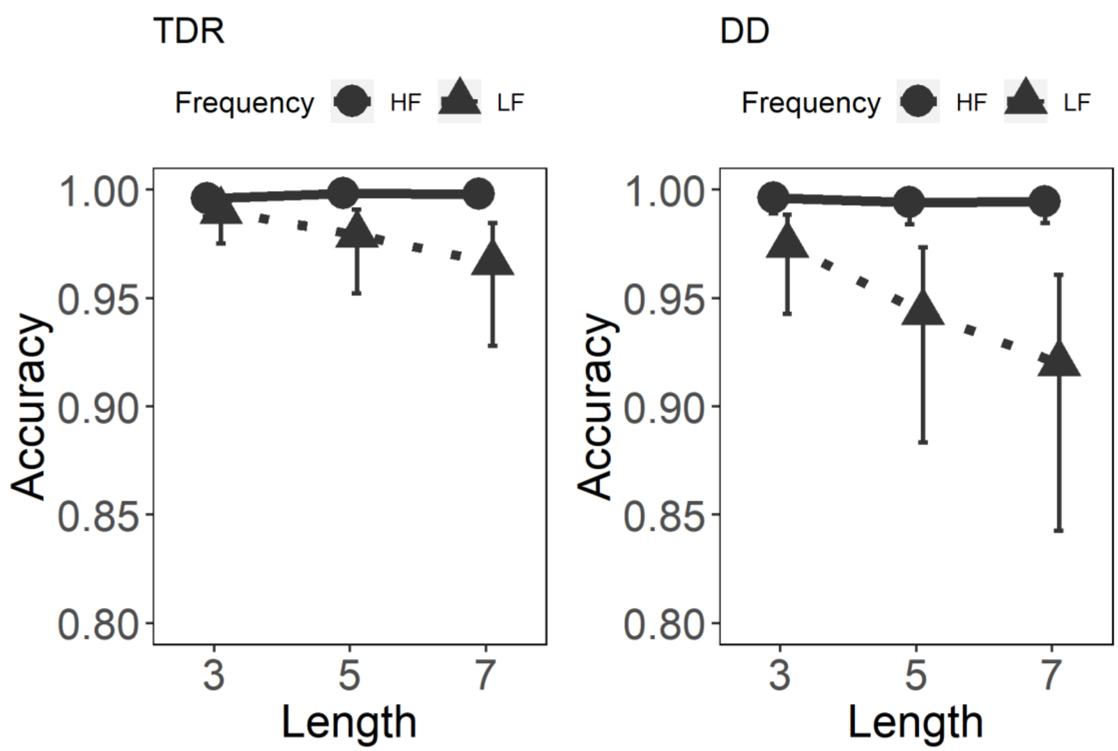

Figure 2.3. Error rates in the two groups in each individual condition. TDR = typical developing readers; DD = developmental dyslexics; HF = high frequency; LF = low frequency.

2.5.4 Nonword reading

2.5.4.1 *Reaction times*

Results for the GLMM on nonword RT are displayed in Figure 2.4. Significant main effects were observed for Group, $F(1, 34) = 12.60$, $p < .001$, and Length, $F(3, 63) = 12.52$, $p < .001$. A significant interaction was observed for Group × Length, $F(3, 2132) = 16.20$, $p < .001$. The results of this nonword reading task demonstrate that the DD group was affected by nonword length, with significant differences between lengths three and five ($t = -6.80$, $p < .001$), lengths three and six (t

= -7.48, $p < .001$), lengths four and five ($t = -4.70$, $p < .001$), and length four and six ($t = -5.35$, $p < .001$). No differences were present between length three and four ($p = .413$). The TDR group did not show any length effects ($p \geq .962$). Post-hoc analyses for the interaction are presented in Table 2.4.

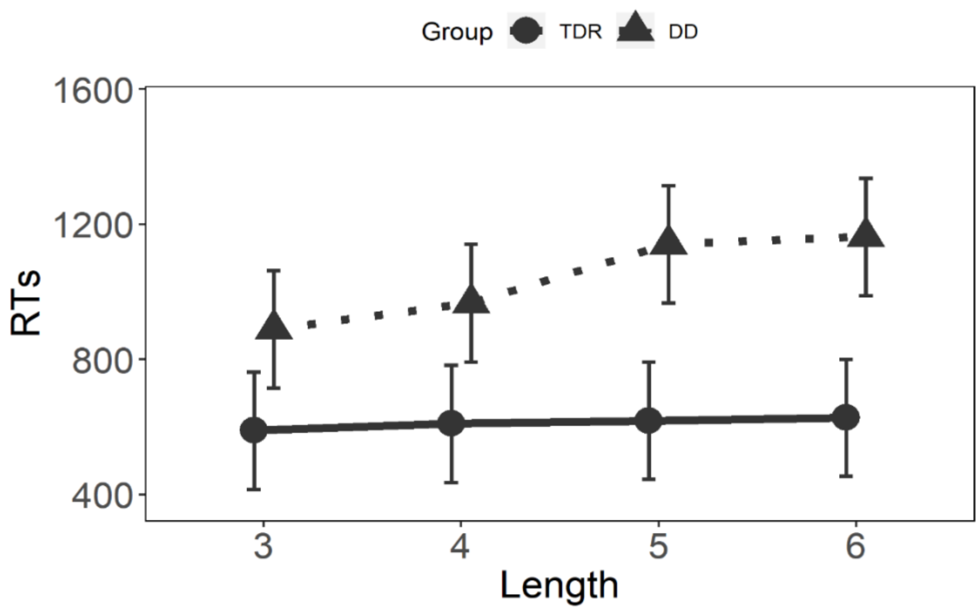

Figure 2.4 Two-way interaction on nonwords. TDR = typical developing readers; DD = developmental dyslexics; RT = reaction times.

Table 2.4. Nonwords post-hoc comparisons on the raw data using Tukey correction.

	Contrast	Estimate	SE	t ratio	p value
1	3,TDR - 4,TDR	-19.98	35.77	-0.56	0.999
2	3,TDR - 5,TDR	-29.27	35.82	-0.82	0.992
3	3,TDR - 6,TDR	-38.17	35.78	-1.07	0.962
4	3,TDR - 3,DD	-299.85	123.35	-2.43	0.257
5	3,TDR - 4,DD	-377.27	125.21	-3.01	0.078
6	3,TDR - 5,DD	-551.27	125.31	-4.40	0.002
7	3,TDR - 6,DD	-573.52	125.19	-4.58	0.001
8	4,TDR - 5,TDR	-9.30	35.72	-0.26	1.000
9	4,TDR - 6,TDR	-18.19	35.68	-0.51	1.000
10	4,TDR - 3,DD	-279.87	125.17	-2.24	0.354
11	4,TDR - 4,DD	-357.29	123.36	-2.90	0.102
12	4,TDR - 5,DD	-531.29	125.28	-4.24	0.003
13	4,TDR - 6,DD	-553.54	125.16	-4.42	0.002
14	5,TDR - 6,TDR	-8.90	35.73	-0.25	1.000
15	5,TDR - 3,DD	-270.58	125.18	-2.16	0.396
16	5,TDR - 4,DD	-347.99	125.20	-2.78	0.130
17	5,TDR - 5,DD	-522.00	123.46	-4.23	0.003
18	5,TDR - 6,DD	-544.24	125.18	-4.35	0.002
19	6,TDR - 3,DD	-261.68	125.17	-2.09	0.438
20	6,TDR - 4,DD	-339.09	125.19	-2.71	0.150
21	6,TDR - 5,DD	-513.10	125.29	-4.10	0.005
22	6,TDR - 6,DD	-535.34	123.34	-4.34	0.002
23	3,DD - 4,DD	-77.41	36.68	-2.11	0.413
24	3,DD - 5,DD	-251.42	36.99	-6.80	0.000
25	3,DD - 6,DD	-273.66	36.59	-7.48	0.000
26	4,DD - 5,DD	-174.01	37.05	-4.70	0.000
27	4,DD - 6,DD	-196.25	36.65	-5.35	0.000
28	5,DD - 6,DD	-22.24	36.95	-0.60	0.999

Note. TDR = typical developing readers; DD = developmental dyslexics.

2.5.4.2 Z-scores

Results for the GLMM on nonword z-scores are displayed in Figure 2.5. A significant main effect was observed for Length, $F(3, 63) = 6.21$, $p < .001$, with no effect of Group, $F(1, 2160) = 1.19$, $p = .276$. This latter result is not surprising since all individual performances have been centred to the zero through the z-score transformation. A significant interaction was observed for

Group × Length, $F(3, 2160) = 12.32$, $p < .001$. These results confirmed those obtained with the raw data. Post-hoc analyses on the interaction are presented in Table 2.5.

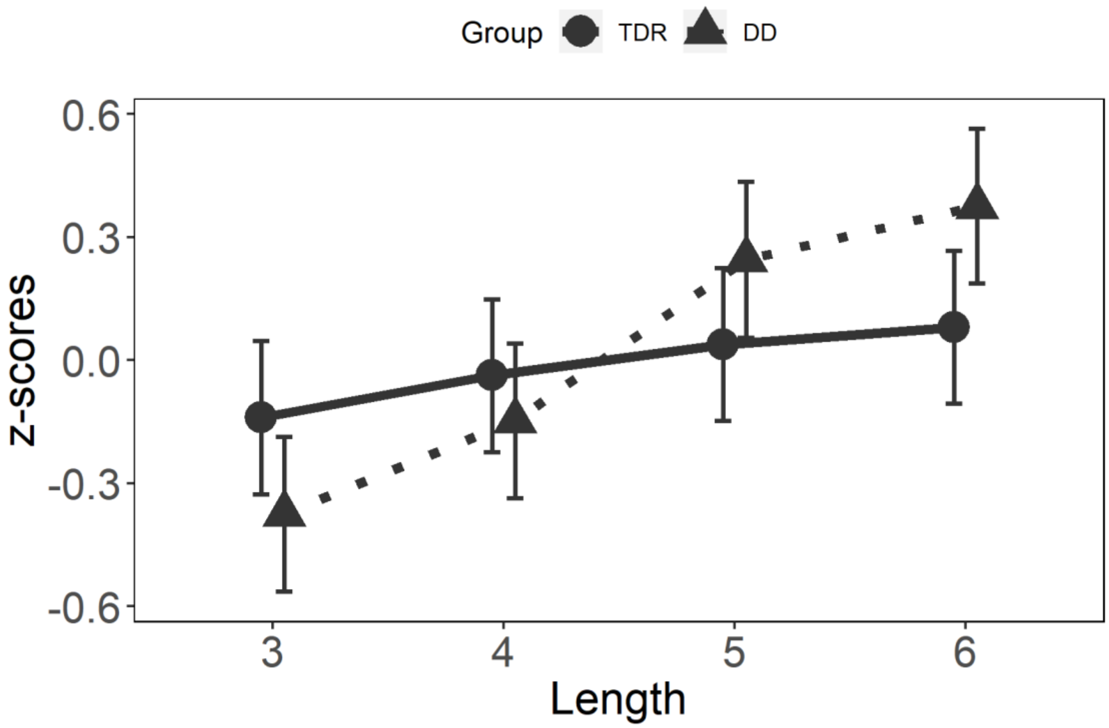

Figure 2.5. *Two-way interaction on z-scores on nonwords. Higher z-scores reflect lower performance. TDR = typical developing readers; DD = developmental dyslexics.*

Table 2.5. Nonwords post-hoc comparisons on the z-scores using Tukey correction.

	Contrast	Estimate	SE	t ratio	p value
1	3,TDR - 4,TDR	-0.10	0.13	-0.76	0.994
2	3,TDR - 5,TDR	-0.18	0.13	-1.33	0.886
3	3,TDR - 6,TDR	-0.22	0.13	-1.64	0.726
4	3,TDR - 3,DD	0.23	0.07	3.27	0.024
5	3,TDR - 4,DD	0.01	0.14	0.05	1.000
6	3,TDR - 5,DD	-0.38	0.14	-2.83	0.101
7	3,TDR - 6,DD	-0.52	0.14	-3.81	0.006
8	4,TDR - 5,TDR	-0.08	0.13	-0.56	0.999
9	4,TDR - 6,TDR	-0.12	0.13	-0.87	0.988
10	4,TDR - 3,DD	0.34	0.14	2.49	0.212
11	4,TDR - 4,DD	0.11	0.07	1.54	0.788
12	4,TDR - 5,DD	-0.28	0.14	-2.08	0.438
13	4,TDR - 6,DD	-0.41	0.14	-3.05	0.058
14	5,TDR - 6,TDR	-0.04	0.13	-0.31	1.000
15	5,TDR - 3,DD	0.41	0.14	3.05	0.058
16	5,TDR - 4,DD	0.19	0.14	1.37	0.867
17	5,TDR - 5,DD	-0.21	0.07	-2.83	0.087
18	5,TDR - 6,DD	-0.34	0.14	-2.49	0.213
19	6,TDR - 3,DD	0.45	0.14	3.36	0.024
20	6,TDR - 4,DD	0.23	0.14	1.68	0.698
21	6,TDR - 5,DD	-0.16	0.14	-1.21	0.927
22	6,TDR - 6,DD	-0.30	0.07	-4.13	0.001
23	3,DD - 4,DD	-0.23	0.14	-1.67	0.707
24	3,DD - 5,DD	-0.62	0.14	-4.53	0.000
25	3,DD - 6,DD	-0.75	0.14	-5.52	0.000
26	4,DD - 5,DD	-0.39	0.14	-2.87	0.091
27	4,DD - 6,DD	-0.52	0.14	-3.84	0.005
28	5,DD - 6,DD	-0.13	0.14	-0.96	0.979

Note. TDR = typical developing readers; DD = developmental dyslexics.

2.5.4.3 *Errors*

Results for the GLMM on nonword errors are displayed in Table 2.1. A significant main effect was observed for group only, Group, z = -3.03, p = .002, reflecting the fact that the TDR group was more accurate than the DD group.

2.6.Discussion

The aim of this study was to investigate whether the effect of word length, usually investigated in adult DD readers of a transparent orthography, may also characterise the reading of English individuals with DD. In this study, we wanted to verify whether participants with DD showed an over reliance on the sub-lexical route, with a consequent increase in the time needed to read words and nonwords of increasing length (i.e., WLE). For this reason, we compared a group of participants with DD to a group of TDRs in word and nonword reading tasks.

The results of this study indicate that participants with DD did indeed present with a strong WLE, compared to TDRs, in both word and nonword reading, which was particularly evident in RTs. The DD group showed a marked decrease in speed of reading as a function of the number of letters in a word. These results are similar to those observed with adult participants in transparent orthographies (Davies et al., 2007; Richlan et al., 2010b; Suárez-Coalla & Cuetos, 2015; Zoccolotti et al., 2005) and with children reading English (Ziegler et al., 2003). A possible explanation for these results may be that participants in the DD group predominantly rely on a serial analysis of the item, remaining anchored to a sub-lexical reading strategy, which results in slower and more effortful reading. For the word reading task, intriguingly, the marked differences in the DD group were in low frequency words, particularly between length three and length seven and between length five and length seven, whereas no statistically significant differences were found between different lengths in the high frequency condition, as shown by the post-hoc comparisons (see Table 2.2). These results may indicate that the DD group employed larger units to read familiar words whereas, they appear to switch to smaller units when reading longer unfamiliar words.

The use of larger and smaller units in reading is postulated by the grain size theory (Ziegler & Goswami, 2005). The grain size hypothesis assumes that readers of inconsistent orthographies rely to a greater extent on larger units or grain sizes (e.g., syllables or even whole words), whereas readers of more consistent orthographies such as Italian, tend to rely on smaller grain sizes (e.g., graphemes) with the reading output primarily based on grapheme-phoneme correspondence. That is, the opaquer the orthography, the larger the units employed in reading. Participants with DD were affected by the frequency of the words with familiar words being read better than unfamiliar words at each length considered. This pattern is consistent with the employment of a lexical route by the DD group to read familiar words. These findings were confirmed by the z-score analyses and mirrored those found with adult DDs reading in a transparent orthography (see e.g., Yael, Tami, & Tali, 2015).

Aspects of the TDR group performance are also interesting to note. In contrast to earlier studies (e.g., Balota et al., 2004), we did not find any significant WLE for words or nonwords. Our results fit well with previous research where WLE has not been found among adult English readers, except in studies which employ a large number of items and lengths (see Marinelli et al., 2016 on this point). However, the results obtained with the z-scores showed that low frequency seven letter words differed from the other lengths. This result may indicate that the TDR group struggle to read long, unfamiliar words, and hence the TDR performance might be affected by the length of the words.

Intriguingly, the TDR group did not show any advantage in reading high frequency words compared to low frequency words (i.e., frequency effect). We can speculate that the employment of larger units by the TDR group might determine the almost total absence of advantage in reading high frequency words compared to low frequency words. In fact, even if a difference is noticeable in terms of means in RT between low frequency and high frequency words, such difference is not statistically significant, except in the case of the seven letter low frequency condition and only in the z-scores (see Table 2.3). Nevertheless, it is worth noting that this result might be due to the effects of the transformation in z-scores.

Overall, the results obtained from the z-score transformation are consistent with those obtained using the RT. However, it is worth stating that in this particular case z-score transformation might be somewhat problematic. It has been argued that to the extent that the product of intrinsic variability and processing rate differs across individuals, the z-score transformation will be differentially biased for individuals (Faust, Ferraro, Richard, Balota, Spieler, 1999). In this study, we found that the variability in the TDR group was much smaller, compared to the variability in the DD group. Therefore, when the raw scores are transformed to z-scores in the TDR group, even very small differences tend to be magnified. Such an effect seems to reflect more differences in the variance than an intrinsic difference between the two groups.

TDRs seem to read familiar words by directly accessing the orthographic representation of the word (whole word recognition strategy) and unfamiliar words through the employment of large chunks such as the pattern of letters, syllables or rimes (e.g., Brown & Deavers, 1999). As previously illustrated, the inconsistency of English, in which the correspondence between letters and sounds is not always predictable, leads readers of this orthography to rely on a larger grain size to read. Indeed, the employment of smaller grain sizes by English readers is more likely to result in errors. The present results are therefore consistent with previous accounts of the use of larger units and a parallel processing mode in English readers (Marinelli et al., 2016; Ziegler & Goswami, 2005). Furthermore, the use of larger units in this group seems to help them to read fast even unfamiliar words, showing a minimum and not statistically significant frequency effect. DD participants, instead, seem to employ smaller grain sizes to read longer and unfamiliar words, which in turn cause an increase in the response latency and the LE. However, the frequency effect showed by such participants seems to highlight that they are still able to employ a parallel processing of the words when they are familiar.

Some useful insight can also be drawn by considering accuracy rates. Both groups were more accurate in reading high than low frequency words. This frequency effect shown by DDs also in RTs confirms the availability of the lexical route in the DD group (Barca et al., 2006). Furthermore, the largest number of errors for both groups was in the low frequency set of five and seven letter lengths. This reflects the fact that in an opaque orthography, like English, long unfamiliar words might be more difficult to read than familiar words even for proficient readers, increasing the number of errors.

The nonword reading task, employed to investigate sub-lexical decoding, showed that WLE in RTs were more apparent in the DD group, than in the TDR group. The marked differences in the DD group were detected between shorter nonwords and longer nonwords. Indeed, no significant WLE was found between three letter and four letter nonwords, whereas a difference was found between three letter and five letter, three letter and six letter, four letter and five letter and four letter and six letter nonwords. These results confirm that DDs can employ larger grain sizes to read even shorter nonwords. However, increasing the number of letters results in smaller grain sizes being employed.

Interestingly, the TDR group did not show any WLE in the nonword task, confirming that the employment of larger grain sizes is the prevailing way to read in this group, even when they encounter unfamiliar words. Indeed, the absence of a WLE in the TDR group in this task is entirely consistent with the employment of larger grain sizes in typical readers of opaque orthographies compared to transparent orthographies. As for the accuracy data, the DD group made more errors than the TDR group, whose performance was also high in this task. The results obtained with the raw data were replicated with the z-scores, demonstrating that these findings are robust and might indicate that the DD group struggled with the sub-lexical decoding.

Overall, these findings suggest that the DD group presents with a large length effect in both word and nonword reading, compared to TDRs, who showed very little difference between conditions in all the measures and tasks considered. Although this result seems to point to a deficit of the lexical route and an over-reliance on the sub-lexical route in DD, the frequency effect shown by DDs allows us to speculate that the lexical route is still available to this group. Furthermore, the difficulties shown by DDs in the nonword reading point out that they also struggle in the sub-lexical decoding. In terms of the DRC model, it is possible that the difficulties in DD arise at an earlier stage of the model, in particular at the visual feature or at the letter unit system.

An alternative explanation of the findings comes from studies conducted with patients with pure alexia. As previously mentioned, these patients present with damage to the left fusiform gyrus in the ventral occipito-temporal cortex, an area known as the visual word form area (Dehaene & Cohen, 2011a). This area seems to be involved in pre-lexical processing of visual word forms (e.g., Dehaene, Cohen, Signman, & Vinckier, 2005). Behaviourally, pure alexia is characterised by a slowing of letter/word processing with some participants only able to read words by identifying one letter at a time. Using sensitive non-orthographic visual tests (naming line drawings of objects, novel face matching, checkerboard and kanji character discrimination), these patients also show deficits in pattern discrimination, object naming, and face processing, and are slower as a function of the visual complexity of the stimuli (Roberts et al., 2015, 2013; Woollams, Hoffman, Roberts, Lambon Ralph, & Patterson, 2014). Future research should then investigate whether participants with DD also present with deficits in non-orthographic visual processing using the same tasks (i.e., checkerboard discrimination, novel face matching). If so, the triangle model (Hoffman et al., 2015;

K. Patterson & Lambon Ralph, 1999) might be a more parsimonious account of these results than the DRC model and the application of the domain-general cognitive neuropsychological approach in explaining DD may prove valuable.

Establishing which model best accounts fits our findings is, however, is beyond the scope of this paper. Nevertheless, it would be useful for future studies to test participants with DD on the visual tasks mentioned above, work which we have already begun. This would seem to be particularly relevant since patients with pure alexia present with WLE associated with other visual impairments (e.g., Roberts et al., 2013). Furthermore, similar brain abnormalities (e.g., left vOT) have been noted in DD using different methods including total brain volume, voxel- and surface-based morphometry, white matter, diffusion imaging, brain gyrification, and tissue metabolite (for review see Ramus, Altarelli, Jednoróg, Zhao, & Scotto di Covella, 2018). Consequently, an association seems to exist between the neural bases of dyslexia (acquired and developmental) and visual and phonological impairments. It would also be interesting to compare participants with DD reading different orthographies such as Italian and English (transparent vs. opaque; see Marinelli et al., 2016 on this point).

To summarise, our results have shown that the WLE seems to characterise DD not only in transparent but also in opaque orthographies, like English. This research presents an original contribution to our understanding of DD in English speakers. In fact, in the extant literature, WLE appears to be scarcely evaluated in DD in opaque orthographies and, in particular, in adults with DD. Furthermore, this study clearly showed that participants with DD are severely impaired in RTs, whereas they performed better in terms of accuracy, although this was lower compared to that of the TDR group.

The results of this study provide insight into WLE in adult participants with DD reading in an opaque orthography and show that the WLE is a critical feature in DD regardless of the orthography. Additionally, since WLE is observed in highly educated participants with DD, it might be an aspect to be clinically assessed in adults with DD in higher education and beyond. Previous research indeed has shown a lack of consensus about how university students should be diagnosed, since their performance in achievement tests is often in the average range (e.g., Sparks & Lovett, 2009). These findings might prove fruitful to clinicians working with DD university students, although further research is needed to confirm the results obtained in this study.

3 Visual and phonological impairments in English dyslexic readers

This Chapter has been published as an article in the journal Frontiers in Psychology with the title: " Double trouble – visual and phonological impairments in English dyslexic readers" (Provazza, Adams, Giofrè, & Roberts, 2019).

Chapter 2 showed that highly educated individuals with DD present with a strong length effect in speed only. These results may indicate that the DD sample employed a serial word decoding strategy to read via the sub-lexical route. However, the WLE presented by the DD sample appeared to be stronger for low frequency words than high-frequency words. This suggests that DD are able to use a whole word strategy to read very familiar words and thus the lexical route is, to some extent, functional. An alternative explanation suggests that the slow reading might be caused by impaired visual processing that in turn produces a slow and effortful word reading with a consequent WLE.

Hence, the study presented in this chapter therefore compared DD and matched controls (TDR) on visual tasks to give an account of visual processing impairments in DD. Additionally, according to the phonological deficit hypothesis, a phonological task was employed to compare the performance of the DD and the TDR samples. Finally, given that some evidence showed that phonological processing deficit may be caused by an underlying auditory deficit, auditory processing was also investigated.

3.1.Introduction

Developmental dyslexia (DD) is a neurodevelopmental disorder characterised by difficulties in reading aloud despite normal intelligence and adequate instruction (American Psychiatric Association, 2013). The cognitive basis of DD is thought to be a phonological deficit and, sometimes, this is proposed as the unique cause (Bruck, 1992; Ramus, 2001; Swan & Goswami, 1997; Vellutino, 2004). This view is widely accepted and underpins one of the primary models explaining the reading disorder in DD, the Dual-Route Cascaded model, DRC (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001).

In this model, reading is assumed to involve two major processes, or "routes". First, one can access stored word pronunciations in the phonological lexicon following activation from the orthographic lexicon or semantic system. This lexical process is necessary when reading words with ambiguous or irregular spellings such as *colonel*. Second, reading can occur via a sub-lexical grapheme-to-phoneme conversion process. In contrast to the lexical process, the sub-lexical process can generate plausible pronunciations for regular words or phonologically plausible nonwords but will produce regularisation errors for irregular words (e.g., *colonel* -> "colernel"; *yacht* -> "yatched"; *sugar* -> "sudger").

Although several subtypes of DD have been described (Castles, Bates, & Coltheart, 2006; Castles & Coltheart, 1993; Friedmann & Coltheart, 2016) there are two strands of evidence that point to some degree of independence between lexical and sub-lexical routes (Castles et al., 2006). First, developmental surface dyslexia is characterised by a difficulty in reading irregular words due to a deficit in the lexical route (Castles, 1996; Job, Sartori, Masterson, & Coltheart, 1984; Zoccolotti et al., 1999). Second, phonological dyslexia is characterised by a difficulty in reading unfamiliar words or nonwords due to a deficit in the phonological or sub-lexical route (Rack, Snowling, & Olson, 1992; Snowling, 1981; Snowling & Hulme, 1989; Temple & Marshall, 1983b).

Despite evidence indicating that impaired phonological processing represents the core deficit in DD, which may lie within these linguistic routes, there is little consensus regarding the specific mechanisms underlying lexical and sub-lexical processes and the heterogeneity of the difficulties presented by individuals with DD. In fact, there is evidence demonstrating that DD may also be characterised by a deficit in different domains, such as auditory and visual processing.

Many studies have demonstrated that some individuals with DD may present with an auditory deficit. For instance, Tallal (1980) proposed that impaired processing of brief sounds in poor readers can affect speech perception in these cases (Fraser, Goswami, & Conti-Ramsden, 2010; Heiervang, Stevenson, & Hugdahl, 2002; Molinaro, Lizarazu, Lallier, Bourguignon, & Carreiras, 2016; Rey, De Martino, Espesser, & Habib, 2002; Tallal, 1980; Wright et al., 1997). Auditory deficits are somewhat independent from phonology, but nevertheless play a role in the severity of the observed phonological deficit (see Ramus, 2003b for an extensive literature review on this aspect).

More striking evidence of the heterogeneity of DD comes from studies that show not all individuals with DD manifest phonological impairments (Bosse et al., 2007b; Jones, Branigan, & Kelly, 2008; Lobier et al., 2012). These findings raise the interesting possibility that different performance patterns might actually reflect distinct underlying mechanisms, rather than differences in the processes or relationships within and between the two routes (Lobier et al., 2012; Stein, 2018b; Stein & Fowler, 1981; Valdois et al., 2003, 2004).

Furthermore, individuals with DD may struggle to process visual stimuli, with some presenting with dysfunction in visuo-spatial attention (Stein & Walsh, 1997; Vidyasagar &

Pammer, 2010). This is often present with an asymmetrical distribution of spatial attention in the two visual fields, such that one is unable to inhibit information from the right visual field and focus attention on the centre of gaze (e.g., Boden & Giaschi, 2007; Martin & Lovegrove, 1984). This pattern of difficulties may disrupt allocation of attention across letters and is generally attributed to a deficit of the magnocellular pathway, and in particular the dorsal pathway, which is involved in the analysis of motion perception (see e.g., Ramus, 2003 for a review of the magnocellular deficit in DD). However, despite evidence showing that the magnocellular deficit can contribute to DD, it remains a controversial and hotly debated issue. In fact, there is no clear evidence that a deficit in the magnocellular pathway can contribute to the reading difficulties in DD, independently of phonological impairments. Moreover, a deficit in the magnocellular pathway has been reported in the scenario of phonological dyslexia but not in surface dyslexia, leaving open the question of what causes this subtype of dyslexia (e.g., Spinelli et al., 1997; Valdois et al., 2004).

Theories explaining deficits in visual attention span underpinning surface dyslexia have contributed to the debate with the most prominent of these being work by Bosse and colleagues (Bosse et al., 2007). The visual attention span hypothesis posits that difficulties in DD are a consequence of a deficit in visual processing. In this vein, the visual attention span hypothesis underpins the existence of visual system impairment in this population (Frey & Bosse, 2018; Lobier et al., 2012; Zoubrinetzky, Collet, Serniclaes, Nguyen-Morel, & Valdois, 2016).

The visual attention span theory is derived from the connectionist multi-trace memory model of reading (Ans, Carbonnel, & Valdois, 1998) and postulates the existence of two reading procedures which are characterised by different “attentional windows” – the analytic (serial) and global (parallel) procedures. The analytic mode uses a narrow attentional window or "spotlight" which serially processes orthographic sub-units (letters or letter combinations) within the word. During this mode, phonological outputs corresponding to each sub-unit are generated successively and have to be maintained in a buffer (memory trace) for phonological production. The global mode uses a wide attentional window or "floodlight" which permits automatic recognition or parallel processing of the whole word during reading aloud, and thus generates the entire phonological output without involvement of the buffer. In this framework, visual attention span is defined as the number of elements (letter units) processed simultaneously (Lallier & Valdois, 2012).

Familiar words are generally processed through the global mode, employing a wide visual attentional window, whereas unfamiliar words are processed through the analytic mode, employing a narrow attentional window – this is because more attention is needed to generate phonological representations from a combination of unfamiliar letter units. If the normal visual attention span is reduced, reading becomes reliant on the analytic mode. Due to the inability of this mode to generate the entire output, irregular word reading becomes slow and regularisation errors may occur. Hence, this theory is able to account for word recognition difficulties in one sub-group of individuals with DD independently of phonology, conceptualised as surface dyslexia, whereas word recognition difficulties in individuals with phonological dyslexia might be better captured by phonological deficits (Bosse et al., 2007; Lobier et al., 2012; Stefanac, Spencer-Smith, Brosnan, Castles, & Bellgrove, 2019; Valdois et al., 2003; Zoubrinetzky, Bielle, & Valdois, 2014; Zoubrinetzky et al., 2016).

Taken together, these findings support the claim that individuals with DD may present with impairments in the visual domain that are not restricted to word processing. Studies investigating visual processing of non-orthographic stimuli (e.g., faces and objects) have indeed demonstrated atypical performance, which strengthens the hypothesis that a visual impairment may characterise some types of DD (Gabay, Dundas, Plaut, & Behrmann, 2017; Robotham & Starrfelt, 2017; Sigurdardottir, Fridriksdottir, Gudjonsdottir, & Kristjánsson, 2018; Sigurdardottir, Ívarsson, Kristinsdóttir, & Kristjánsson, 2015). Such evidence cannot be fully accounted for by lexically-based visual word recognition models (i.e., the DRC model).

An alternative approach which might accommodate some of these findings proposes that disorders of reading do not occur in isolation but are an emergent effect of damage to one of three primary systems (vision, phonology, semantics), or impaired input to them, to which reading may be more susceptible (Hoffman, Lambon Ralph, & Woollams, 2015; Patterson & Lambon Ralph, 1999). The triangle model is an instantiation of the primary systems hypothesis, and proposes that the same computational elements, in various combinations, support different reading and non-reading activities: (1) vision, which with respect to reading mediates knowledge about orthographic word form but also processes non-orthographic visual stimuli; (2) phonology – the internal representation of word sound, also utilised by any form of verbal input or output including naming and repetition; and (3) semantics – word meaning.

Reading is accomplished by the division of labour between the three systems. In particular, a mapping between vision and phonology (V>P) permits reading of regular words with a high speech-sound correspondence (e.g., *mint*) or high frequency irregular words (e.g., *have*), whereas irregular words with a less regular speech-sound correspondence (e.g., *colonel*, *pint*) are supported by the semantic system (V>S>P) (Woollams, 2014).

Despite evidence confirming this alternative view in accommodating the impairments in some of the acquired dyslexias (e.g., co-occurrence of phonological dyslexia in comorbidity to non-fluent aphasia see Farah, 1996; visual impairments in pure alexia see Roberts et al., 2013; the co-occurrence of surface dyslexia with semantic deficits see Woollams et al., 2007), there is insufficient evidence to establish the capacity of this model to also explain impairments in DD (Woollams, 2014). A prediction that follows from this model is that individuals with DD, when tested appropriately, will show deficits in non-reading tasks, depending on which primary system is impaired. For instance, a degraded incoming visual signal caused by a narrow attentional window will affect reading and other visual tasks that demand similar processing (Gabay et al., 2017). Moreover, due to the interactive nature of the model, it is also predicted that a dysfunctional visual system may affect performance of other types of task that necessitate visual processing such as visuo-spatial working memory.

Working memory (WM) is a limited capacity system, which enables the temporary storage and maintenance of information (Baddeley & Hitch, 1974; see Cornoldi & Giofrè, 2014 for a review). Several WM models are available but the classical tripartite model, which distinguishes between two slave systems (verbal and visuo-spatial) and a central executive component, has received substantial support in the literature (Baddeley, 1986; Cornoldi & Giofrè, 2014). Deficits in the verbal component seem to be quite severe and a core feature of performance in DD (Peng & Fuchs, 2016; Toffalini, Pezzuti, & Cornoldi, 2017). Hence, previous studies have focused on the verbal domain (e.g., Majerus & Cowan, 2016), with the visuo-spatial component receiving little attention (with some exceptions see Cowan et al., 2017; Smith-Spark & Fisk, 2007; Smith-Spark et al., 2003). It therefore remains to be determined whether, as with acquired disorders of reading, visuo-spatial working memory (VSWM) impairments can explain an additional portion of the variance in word reading in DD after controlling for verbal WM skills.

According to the primary system hypothesis, a number of predictions can be made. First, individuals with DD should also present with visual deficits, as evidenced in patients with acquired dyslexia (i.e., pure alexia, see e.g., Roberts et al., 2013). To test this prediction, we used visual discrimination tasks with unfamiliar objects – checkerboards and Kanji characters (see Methods section and Figures 3.2 and 3.3 for detailed information of these tasks). We chose to use non-orthographic stimuli to assess visual processing *per se* and to avoid underestimating the severity of the visual impairment. For instance, using familiar stimuli might result in top-down semantic support which may compensate for, or boost activation of, an impaired visual system (Plaut, 1999). Moreover, studies conducted on DD children in Japan, a logographic orthography showed that these children exhibited difficulties in reading and writing Kanji (Kaneko, Uno, Kaga, Inagaki, & Haruhara, 1997; Uno, Kaga, & Inagaki, 1995). The authors argued that such difficulties might be explained by problems in visual or visuo-spatial processing. Indeed, the role of phonology may be less prominent in orthographies in which the units employed to read are coarser than the single grapheme (Wydell & Butterworth, 1999b). Thus, the difficulties shown by individuals with DD in those orthographies might be underpinned by a compromised visual system. What we aim to investigate in this study is the extent to which an impairment in visual processing may also characterise DD reading of alphabetic orthographies.

Second, impairments in WM are not only limited to the verbal domain but can also affect the visuo-spatial aspects, in particular those that place maximal demands on attentional control. For this reason, we used VSWM tasks that were demanding in terms of attentional control (see Methods section and Figure 3). We expected that a) a low-level impairment in visual processing will affect the performance of individuals with DD in VSWM tasks and b) poor performance will be exaggerated in tasks that require more attentional control.

Third, DD should be considered as a complex disorder encompassing general processing deficits in both phonological and visual domains. Hence, phonology was measured in accordance with the predominant literature indicating deficits in this skill in individuals with DD. Finally, DD could be also characterised by a low-level auditory deficit. Indeed, some research has shown that impaired processing of brief sounds might be detrimental to speech perception, thus aggravating the phonological deficit (Molinaro et al., 2016; e.g., Wright et al., 1997).

3.2 Method

3.2.1. Participants

Eighteen university students with DD (5 males; age range 19-27; M_{years}= 21.8; SD= 2.29) participated. All were first language English speakers and in receipt of a formal diagnosis of dyslexia (supplied by a registered assessor of SpLD) as required for access arrangements and additional support in UK HE institutions. Participants with DD have been contrasted to a typical developing readers (TDR) group comprising 18 students (7 males; age range 19-28; M_{years}=21.8; SD=2). The two groups did not differ statistically for gender, $\chi^2(1) = 0.50$, $p = .480$, Cramer's $V = .118$, or age, $F(1, 34) = 0.02$, $p = .878$, $\eta^2_p = .001$.

The reading level of the two groups was assessed using two reading tasks (word and nonword reading, see Roberts et al., 2010). As expected, participants in the two groups differed statistically with DD performing worse than TDR when reading words, $F(1, 34) = 6.86$, $p = 0.013$, $\eta^2_p = 0.168$, and nonwords, $F(1, 34) = 7.68$, $p = 0.009$, $\eta^2_p = 0.184$.

3.2.2 Materials

3.2.1.1 Visuo-spatial working memory tasks (Mammarella, Caviola, Giofrè, & Szűcs, 2018).

Three VSWM tasks were employed in this study: balloons, sequential matrices and simultaneous matrices (Figure 3.1). Two trials for each span were presented. Partial credit score was used for scoring purposes. This scoring procedure allows for a more precise estimation of the WM capacity of each individual by considering the partial recall, e.g., if a participant correctly recalled 5 out 6 stimuli in the correct order in one trial the score for that trial would be 5 (see Giofrè & Mammarella, 2014; Unsworth & Engle, 2006; 2007; for the statistical rationale). It is worth noting that the current literature disincentive the use of proportion of correct responses or percentages, because they often alter the raw and are somehow more imprecise (e.g., Unsworth & Engle, 2007). For balloons and simultaneous matrices, stimuli were simultaneously presented, therefore the order of recalling was irrelevant for this task. For the sequential matrices span, participants were required to recall the items in the right order of presentation. In this latter task, partial recall was constituted by the sum of the stimuli correctly recalled in the correct order of presentation.

For the balloons task, the stimuli were schematic drawings seen from the front. Initially, a set of two drawings is shown for 4 seconds (Figure 3.1a). Immediately after presentation, the participant has to recognise the target drawings (by clicking on it) within a set comprising three stimuli. Then a set of three drawings was presented for the same length of time and the participant must recognise them among a total of five drawings. From there, three larger sets of drawings were also used. The set of four, five, and six target drawings were placed in groups of six, eight and nine drawings, respectively (min possible score = 0 and max possible score = 40).

In the sequential matrices task, participants were asked to memorise and recall the positions of black cells that appeared for 1 second in different positions on a 5 × 5 grid (Figure 3.1b). After a series of black cells had been presented, participants clicked on the locations where they had seen a black cell appear in the right order. The number of black cells presented in each series ranged from 2 to 8 (min possible score = 0 and max possible score = 72).

In the simultaneous matrices task, participants had to memorise and recall the position of a number of black dots, which appeared simultaneously for 3 seconds on a 5×5 grid (Figure 3.1c). All of these tasks were of increasing difficulty. Participants were presented for 1.5s with a 5 × 5 grid. The number of black dots presented in each grid ranged from 2 to 8. After 3s the initial stimulus was removed, and participants were presented with a blank test matrix in which they had to click on the previously filled squares. The number of black cells presented in each series ranged from 2 to 8 (min possible score = 0 and max possible score = 72).

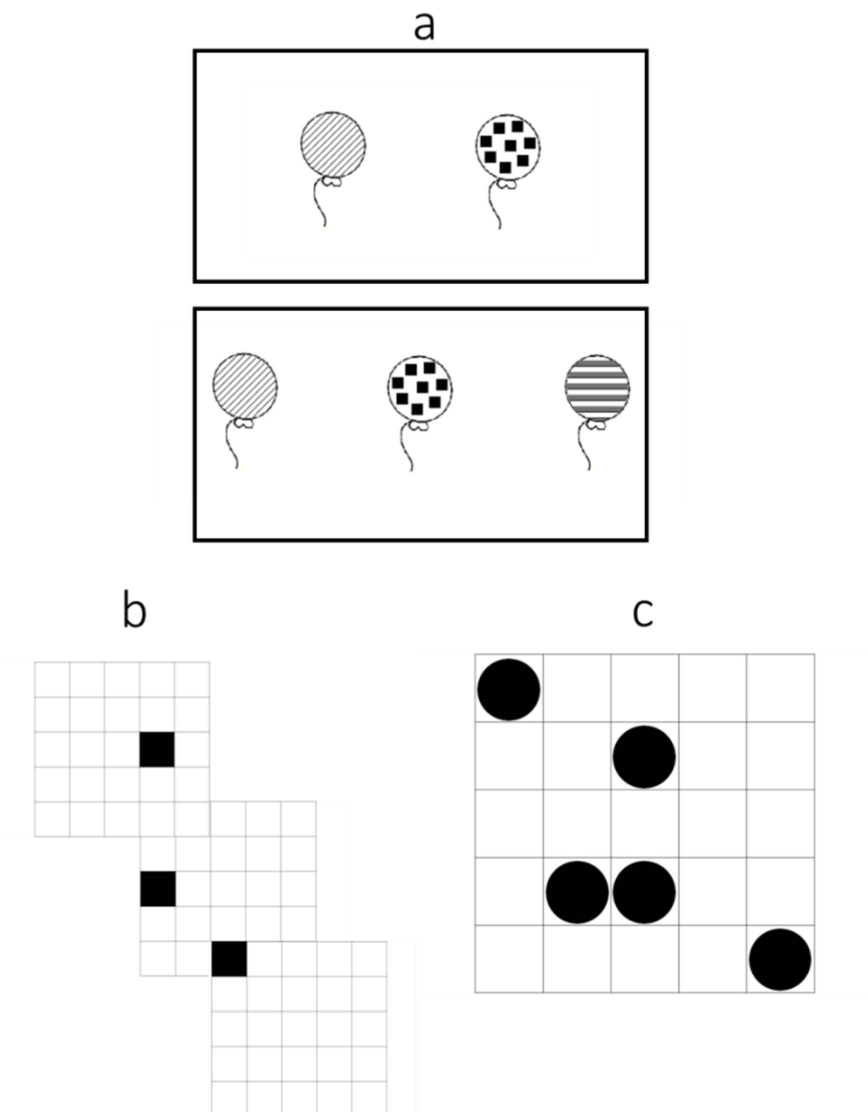

Figure 3.1. Example VSWM tasks for A) balloons, B) sequential matrices, and C) simultaneous matrices.

3.2.1.2 Visual matching tasks (Roberts et al., 2013)

Two visual matching tasks were employed to assess visual abilities and are described below. For each of these tasks, RT and accuracy data were collected.

Checkerboards. A set of 32 black and white checkerboards were used (Figure 3.2). The number of squares in each matrix was either 9 (3×3) or 49 (7×7), forming the visually simple and visually complex sets respectively. Grids were constructed by avoiding placement of blocks of the same colour together or any other regularity in the patterns (that might simplify visual processing). Stimuli were used to form a triad-based matching-to-sample task, in which the probe was flanked above and below by the target and foil. The position (above/below) of target and foil was randomised. Three vertically aligned checkerboards appeared on the screen for each trial. The central checkerboard was the probe stimulus, and the participants had to decide whether the top or bottom checkerboard matched the central one (i.e., they had to identify the target), by pressing two different keys on the keyboard ("N" for the stimulus below and "Y" for the stimulus above). Each participant was required to respond as quickly and accurately as possible.

Kanji Characters. A set of 60 single kanji characters were used (Figure 3.3). Visual complexity was defined in terms of the number of strokes in each character. Characters with 2–4 strokes constituted the simple items, and those with 13 strokes formed the complex set. Again, each target character appeared in a matching-to-sample triad. The probe was placed in the centre with the target and foil above or below. The position of the target was randomised across trials. Three vertically aligned Kanji appeared on the screen for each trial. The central Kanji was the probe stimulus, and the participants had to decide whether the top or bottom Kanji matched the central one (i.e., they had to identify the target), by pressing two different keys on the keyboard

("N" for the stimulus below and "Y" for the stimulus above). Each participant was required to respond as quickly and accurately as possible.

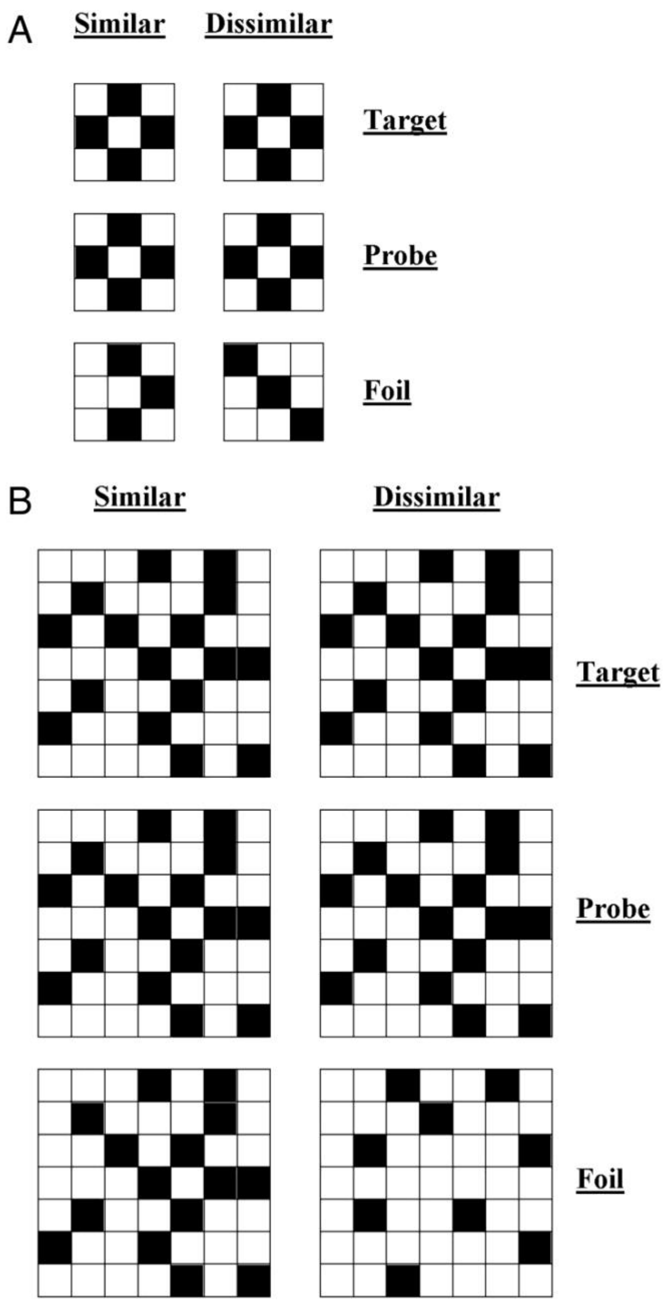

Figure 3.2 Example checkerboard stimuli for (A) visually simple condition and (B) visually complex condition with similar and dissimilar foils (Roberts et al., 2013).

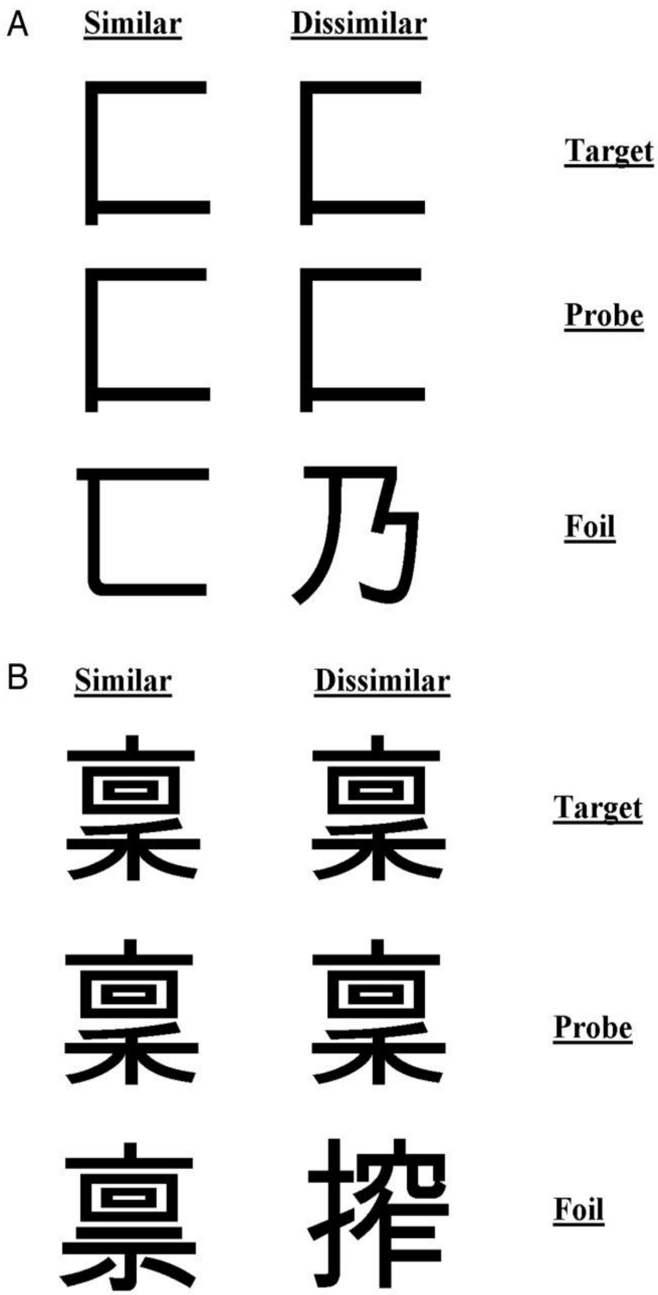

Figure 3.3 Example checkerboard stimuli for (A) visually simple condition and (B) visually complex condition with similar and dissimilar foils (Roberts et al., 2013).

3.2.1.3. Phonological tasks (WAIS IV Wechsler, 2008)

To investigate phonological processing the digit span test was used. This test consists of three subtasks: digit forward, in which participants were instructed to recall as many of the digits as possible in the same order they were presented; digit backward, in which participants had to recall the digits in the reverse order; and digit sequential, which required participants to recall the digits in ascending order of magnitude. The span test score is obtained by summing up the scores in the three span conditions (see Wechsler, 2008 for more detailed information).

3.2.1.4. Auditory matching tasks (Roberts, 2010)

An identical design to the checkerboard and Kanji task was employed. To control for the presence of an impairment in auditory processing, an auditory matching task was employed to assess auditory abilities. This tests purely auditory processing (stripped of meaning, lexical properties etc.). Three tones were presented for each trial. The last tone was the probe stimulus, and the participants had to decide whether the first or the second tone matched the last one (i.e., they had to identify the target), by pressing two different keys on the keyboard ("1" for first stimulus presented and "2" for the second stimulus presented). Each participant was required to respond as quickly and accurately as possible. RT and accuracy data were collected for the task.

3.2.2 Procedure

All tasks were administered using E-Prime 2.0 software (MacWhinney, St. James, Schunn, Li, & Schneider, 2001). Students were assessed individually in a single session lasting approximately 1 hour in a quiet room at Liverpool John Moores University. The study was approved by the RES Committee North West – Liverpool Central (15/NW/0461) and written consent was obtained from all participants.

3.3 Results

Means and standard deviations for both RT and accuracy of the two groups, and group comparisons in terms of Cohen's *d*, are displayed in Table 3.1.

Table 3.1. Mean scores and standard deviations (SD) obtained by the typical developing readers (TDR) and the Developmental Dyslexia. (DD) groups in all tasks

	DD	TDR	Statistical analyses			
			***F*(1,34)**	***p***	**η^2_p**	**Cohen's *d***
VSWM tasks						
Balloons	30.61(4.41)	33.33(3.38)	4.32^{*}	.045	.11	.68
Sequential Matrices	35.17(10.57)	48.17(8.62	16.35^{**}	.000	.32	1.32
Simultaneous Matrices	56.61(6.90)	61.83(5.61)	6.20^{*}	.018	.15	.81
Visual tasks						
Checkerboards RT	2866.34(853.49)	2334.52(525.50)	5.07^{*}	.031	.13	.73
Kanji RT	1826.27(558.80)	1411.08(331.28)	7.35^{*}	.010	.18	.88
Checkerboard ACC	0.94(0.03)	0.96(0.04)	1.90	.177	.05	.45
Kanji ACC	0.95(0.04)	0.97(0.02)	1.81	.187	.05	.44
Verbal task						
Span test	24.20(4.50)	31.61(4.34)	25.18^{**}	.000	.42	1.64
Auditory						
Tone test RTs	661.70(395.60)	436.10(141.68)	5.15	.030	.13	.75
Tone test ACC	0.81(0.11)	0.91(0.06)	11.66^{**}	.002	.25	1.12

Note. TDR = typical developing readers; DD = developmental dyslexics; RT = reaction times; ACC = accuracy; .000 means that the value is zero when approximated to the third decimal. * $p <$ .05, ** $p < .01$.

3.3.1 Data analyses

SPSS (Version 25; IBM, 2017) was used to perform all analyses. Before conducting the discriminant function analysis, issues related to sample size and multivariate normality were addressed (Tabachnick & Fidell, 1996a). The criterion that the sample size of the smallest group should exceed the number of predictors was met. Group size was equal, ensuring multivariate normality.

3.3.1.1 *VSWM tasks*.

A MANOVA was performed comparing VSWM tasks (balloons, sequential matrices, simultaneous matrices) in the two groups (Figure 3.4). A significant effect, $F(3,32) = 6.62$, $p = .001$, $\eta^2_p = .383$, was found, with a large effect size. Participants with DD performed significantly worse than TDR in all the VSWM tasks, with effect sizes ranging from moderate to large. Follow up ANOVAs are presented in Table 3.1.

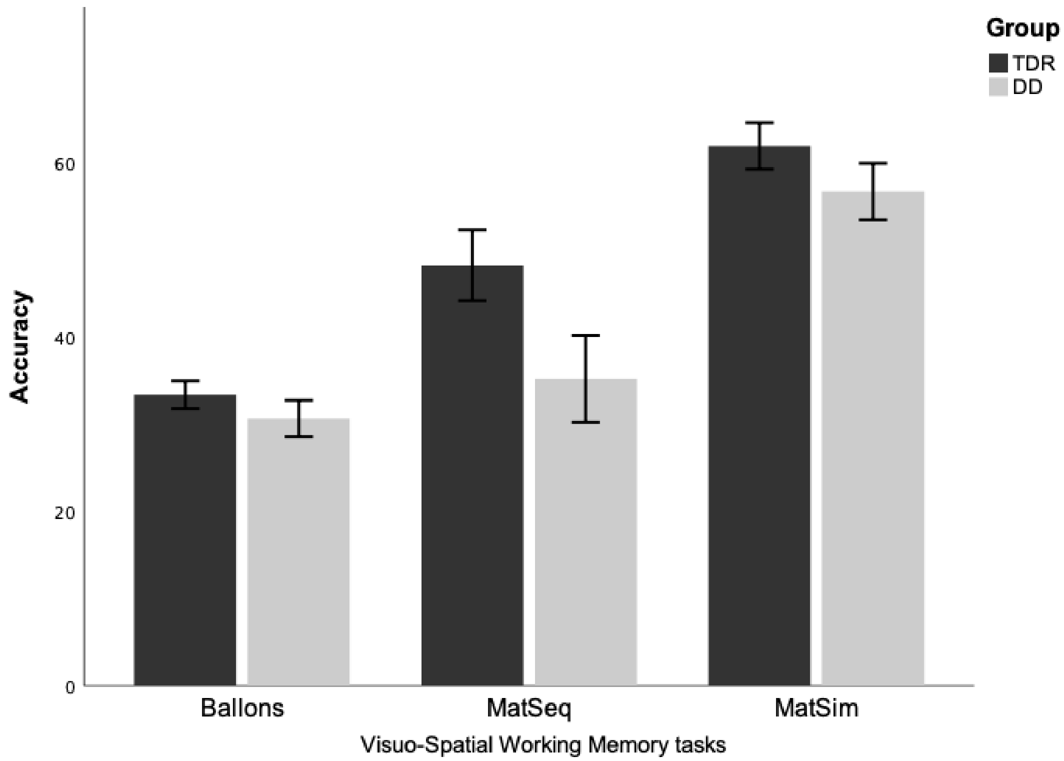

Figure 3.4. VSWM tasks. Error bars represent standard errors. TDR = typical developing readers, DD = developmental dyslexia.

3.3.1.2 *Visual processing*

A MANOVA was performed comparing RTs in the visual tasks (Checkerboards and Kanji – Figure 3.5). A significant effect of Group, $F(2,33) = 3.63$, $p = .037$, $\eta^2_p = .181$, with a medium effect size was identified. Participants with DD performed worse than the TDR group in both tasks, with moderate effect sizes. A MANOVA was also performed for the accuracy in these tasks. The results showed no significant differences between the DD group and TDR group, $F(2,33) = 1.11$, $p = .340$, $\eta^2_p = .063$, with a small effect size. Follow up ANOVAs are presented in Table 3.1.

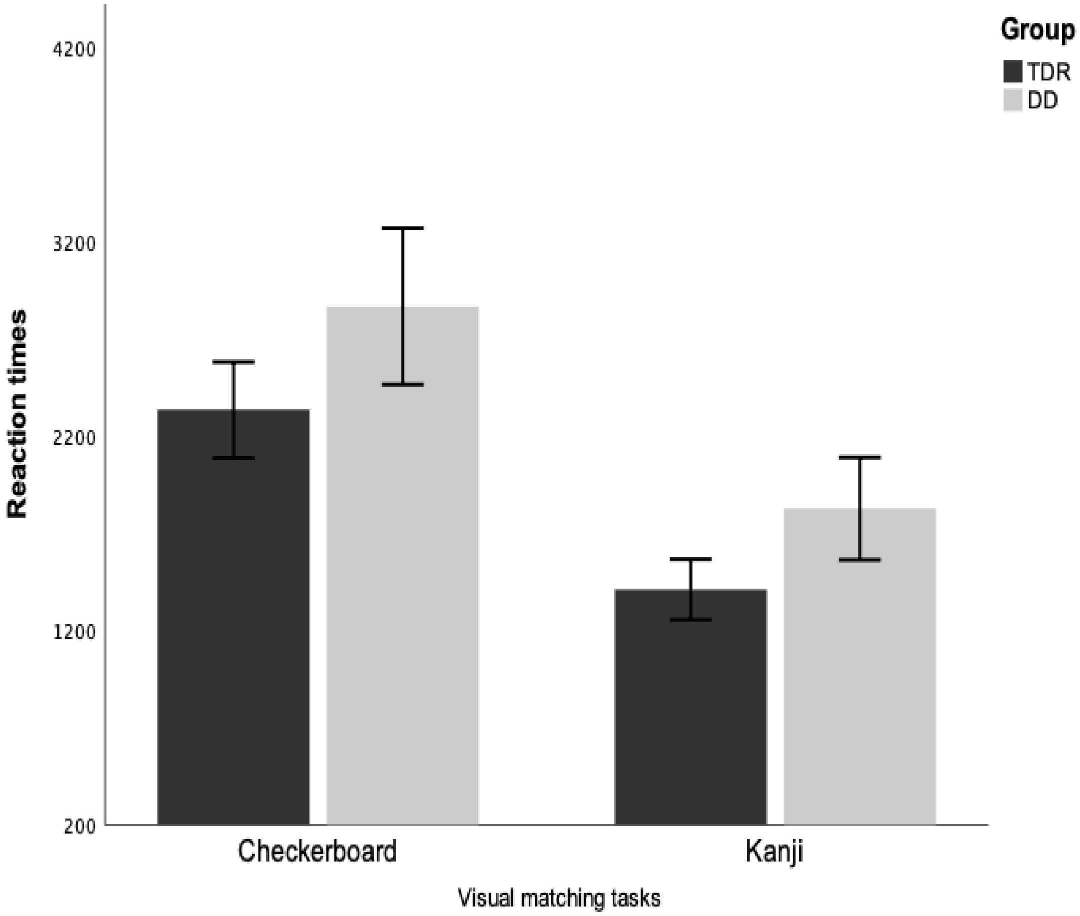

Figure 3.5. RT on visual tasks. Error bars represent standard errors. TDR = typical developing readers, DD = developmental dyslexia.

3.3.1.3 ***Phonological processing***

We performed an ANOVA to compare the performances of the two groups (Figure 3.6). The results showed that the DD group performed worse than TDR group, $F(1,34) = 25.18$, $p <.001$, $\eta^2_p = .426$, with a large effect size.

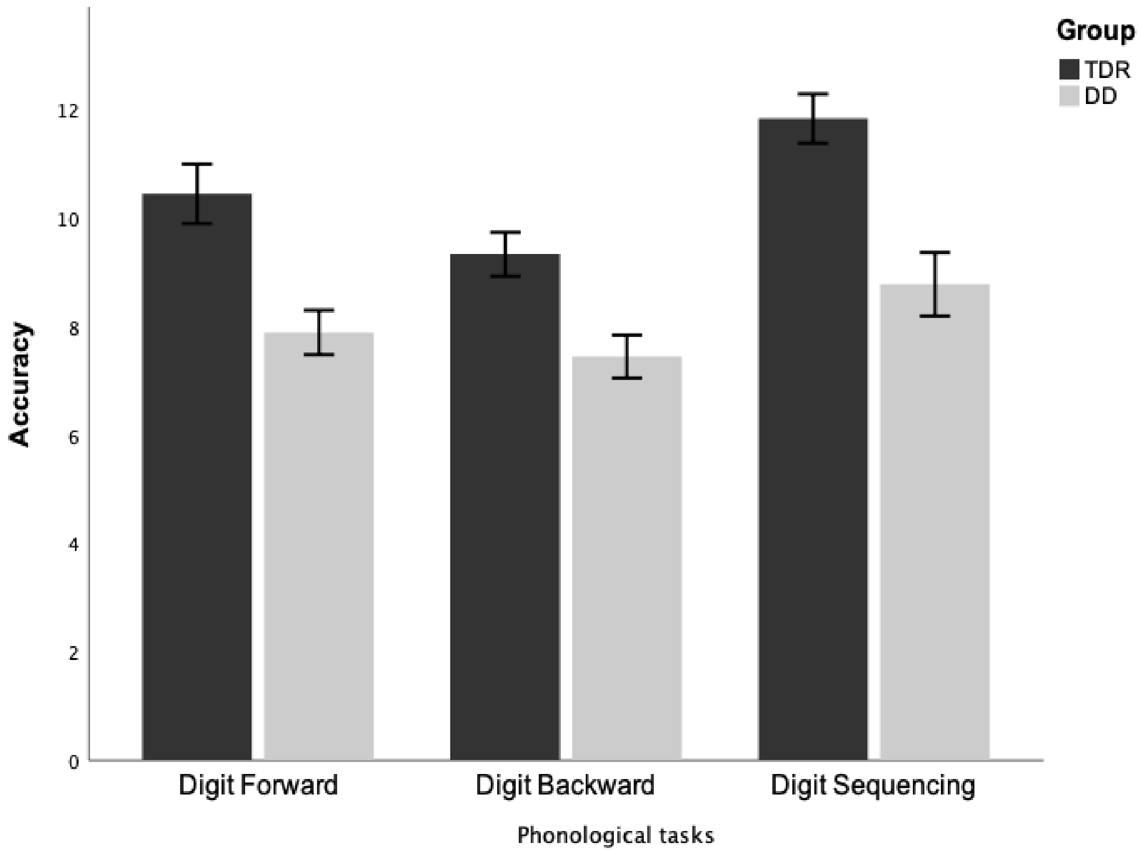

Figure 3.6. Phonological tasks. Error bars represent standard errors. TDR = typical developing readers, DD = developmental dyslexia.

3.3.1.4. ***Auditory processing***. An ANOVA was performed to compare the performances of the two groups in both RTs (Figure 3.7) and accuracy (Figure 3.8). With respect to the RTs, the results showed that the DD group performed worse than TDR group, $F(1, 34) = 5.15$, $p <.030$, $\eta^2_p =.131$ with a medium effect size. The DD group performed worse than TDR group also in accuracy, $F(1, 34) = 11.66$, $p =002$, $\eta^2_p = .255$, with a large effect size.

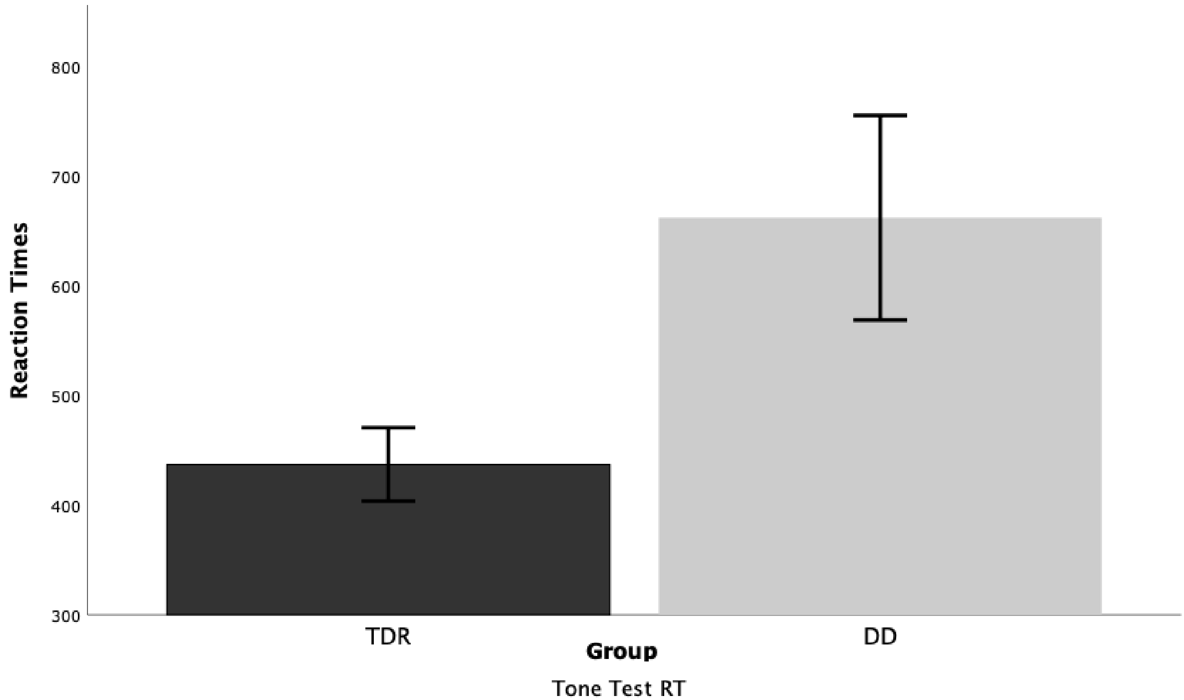

Figure 3.7 Reaction times on auditory tasks. Error bars represent standard errors. TDR = typically developing readers, DD = developmental dyslexics.

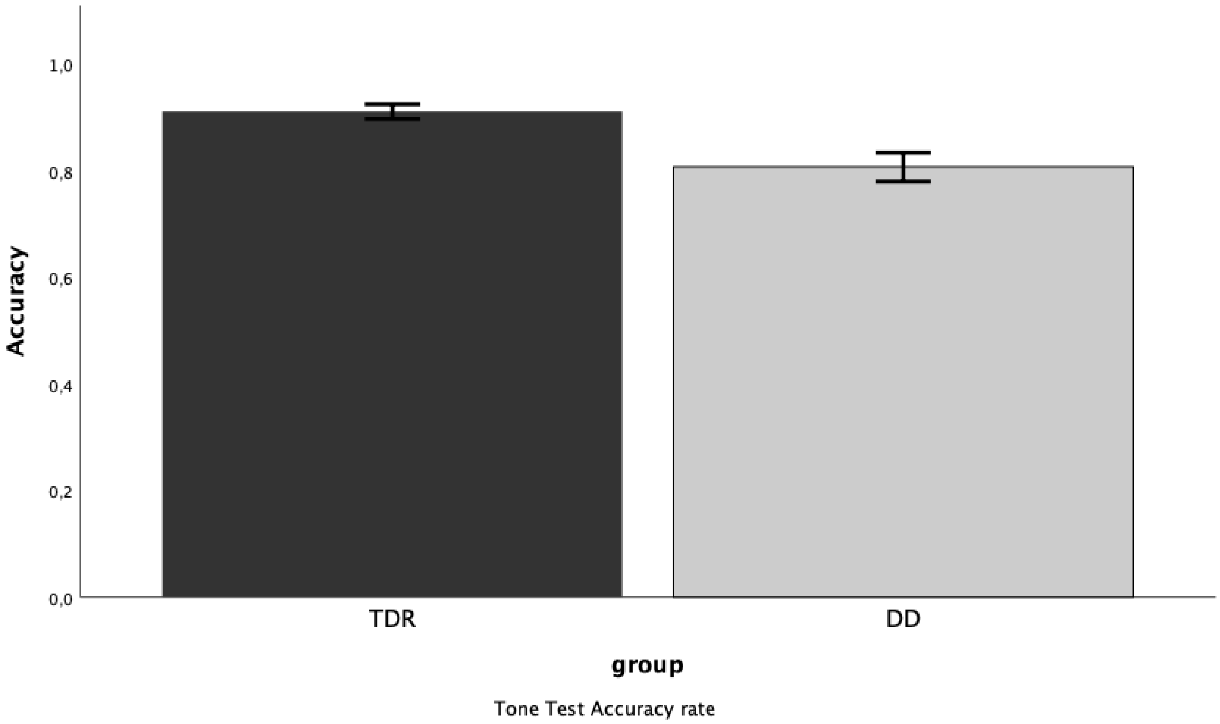

Figure 3.8 Accuracy on auditory tasks. Error bars represent standard errors. TDR = typically developing readers, DD = developmental dyslexics

3.3.2. Discriminant function analysis

Discriminant analysis is generally used to determine which variables discriminate between two or more groups. Discriminant analysis is also used to investigate how variables contribute to group separation, and to what degree. Here, discriminant function analysis was performed to establish which tasks had the greatest discriminatory power to distinguish between participants with DD and TDR. The criterion that the sample size of the smallest group should exceed the number of predictors was met, and the group size was equal, ensuring multivariate normality. The discriminant analysis was conducted with the stepwise method, using all the tasks of the VSWM, visual, verbal and auditory domains. Only a visual matching task (i.e., the Kanji task) and a verbal working memory task (i.e., the span test) were included in the model, with a Wilk's λ =.47, which indicates that these two predictors were the best variables to discriminate between the two groups.

The discriminant function analysis showed a reliable association with both the DD and the TDR group, $\chi^2(2) = 25.03$, $p < .001$. The Kanji task and the span test were able to correctly discriminate 100% of the TDR group (i.e., 18/18) and 83.3% of the DD group (i.e., 15/18). Overall, the model was able to discriminate 91.7% of the participants. This finding indicates that these two tasks, i.e., Kanji and span test, had the greater discriminatory power as compared to all the other tasks included in this study. Thus, performance on tasks from both the phonological and the visual domain is required to discriminate participants with DD from those who have made typical progress in reading.

3.4 Discussion

The aim of this study was to investigate whether individuals with DD present with linguistic impairments only, which are well captured by the DRC model, or if they also present with impairments in the visual domain in addition to phonological impairments, a position that aligns more closely with the triangle model. We aimed to describe such impairments within the framework of the triangle model, an instantiation of the primary system hypothesis. In order to achieve these aims a group of individuals with DD was compared with a matched group of TDRs using a comprehensive cognitive battery, including a number of visual, phonological, and auditory tasks.

The results demonstrated a phonological impairment in the DD group, who performed significantly worse on the span test, with a large effect size. This finding confirms previous evidence highlighting impaired performance compared to controls on phonological tasks (Carroll & Snowling, 2004; Paulesu, 2001; Snowling, 1981). More critically, the DD group also performed worse on VSWM and visual processing tasks. These results indicate that in addition to phonologically-based deficits, individuals with DD also have difficulties in processing visual and visuo-spatial information. This has important theoretical implications, since although it is well established that individuals with DD have difficulties in verbal WM tasks (e.g., Ackerman & Dykman, 1993b; Gathercole et al., 2016), evidence of a visual processing deficit, and VSWM in particular, are scarcely investigated (with some exceptions e.g., Menghini, Finzi, Carlesimo, & Vicari, 2011).

Although the group with DD were impaired on all VSWM tasks, they were disproportionately impaired on one particular task – the sequential matrices. In fact, some visuo-spatial WM models, including for example Cornoldi and Vecchi (2003) and Kane and co-authors (2004) distinguished between tasks requiring different degrees of attentional control. This might explain at least in part why individuals with DD tend to be more impaired in tasks requiring sequential recall (e.g., sequential matrices and digit span), which place maximal demands on attentional control (Cornoldi & Vecchi, 2003). Notably, difficulty with sequential tasks, either verbal or visuo-spatial, also occurs in individuals with other learning difficulties, such as dyscalculia or non-verbal learning disabilities (Bizzaro, Giofrè, Girelli, & Cornoldi, 2018; Mammarella et al., 2018; Mammarella, Giofrè, Ferrara, & Cornoldi, 2013). This supports the view that individuals with DD might struggle with sequential tasks (Helland & Asbj∅rnsen, 2003; Plaza & Guitton, 1997).

As for the non-orthographic visual tasks, with a minimal requirement of WM abilities, the DD group also showed an impairment, particularly in speed of responding. These findings are similar to those obtained with acquired dyslexic patients (Roberts et al., 2013) and are consistent with explanations of a visual deficit contributing to DD. It is worth noting that visual deficits were captured in speed of processing rather than accuracy, and such impairments could easily be missed if only accuracy is measured. Hence, it is important to measure response speed when visual processing is evaluated in DD and in this scenario visual impairments might be more prominent in DD. These findings, along with those obtained in the VSWM tasks, support the claim that a deficit in visual processing may characterise some individuals with DD.

Our study also aimed to investigate whether visual and phonological processing tasks could discriminate between DD and TDR group membership. The discriminant function analysis demonstrated that the digit span and the Kanji tasks were best able to discriminate between the two groups. The fact that both visual and phonological tasks were required for successful discrimination supports a position of both phonological and visual processing skills being important in the dyslexic profile. These findings represent an aspect of novelty and are better accommodated by the triangle model. Indeed, the triangle model is a domain general model explaining reading difficulties in terms of a deficit to a tripartite of basic underlying systems (vision, phonology, and semantics). On this account, DD may occur as a consequence of damage to the phonological and visual systems, which produces difficulties in reading along with deficits in phonological or visual processing.

Taking up this point, individuals with DD performed significantly worse than TDR on the tone test in both accuracy and RTs, with large effect sizes. These findings confirmed those of previous research and indicate the presence of some low-level sensory deficit (Goswami, 2015; Goswami et al., 2002; Marshall, Snowling, & Bailey, 2001). However, auditory tasks do not discriminate between the two groups when the other variables are entered into the equation. This might emphasise that, even though presenting with some low-level sensory deficit, phonological impairments explain a larger proportion of variance. Indeed, when the phonological tasks are entered into the model, they showed better discriminatory power in distinguishing between DD and TDR groups than the auditory task. Such a result, stresses the importance of phonology and not merely auditory processing in adults with DD. Furthermore, it would be interesting to evaluate processing skills in the phonological and visual domains of dyslexic readers within different cultures, particularly those reading different orthographies (e.g., transparent languages such as Italian, see e.g., Provazza, Giofrè, et al., 2019 for some considerations about dyslexia in different languages). Finally, large scale studies should be performed to understand whether dyslexia operates as an umbrella term encompassing several different problems, such as phonological and visual processing (Giofrè, Toffalini, Provazza, Calcagni, et al., 2019).

This study highlights some interesting future research directions. The visual tasks included in this study might require both visual decoding and visual perceptual processing. We are of the view that the visual deficit and visual attention deficit may be overlapping – they both recruit activations of ventral and dorsal visual pathways, but they are, at least in part, distinguishable. Visual tasks in the present study might be more related to some basic visual decoding skills rather than to visual attention span. Further research is needed to disentangle between these two processes, which might reflect different underlying mechanisms. The phonological test used in this task might, in some way, reflect verbal short-term-memory capacities. In fact, it can be argued that the auditory matching tasks also involved short-term memory considering that the presentation is serial as compared to the simultaneous presentation of stimuli in visual matching tasks.

Furthermore, the VSWM tests might also be related with visual short-term memory, verbal short-term memory, and some basic visual decoding. For instance, some tasks seemed not so related to visuospatial attention but exhibited some relationship with memory. This could be accounted for example, by the working memory triarchic model postulated by Baddeley and Hitch (1974), which contains both visual spatial processing and the verbal circle. This is also accommodated by other WM models such as those considering attention as a fundamental part of working memory capacity (see for example Engle, 2010 for an historical perspective). The authors recognise that it is often very hard to distinguish between attention and WM, since very simple tasks might require memory resources whilst at the same time complex span tasks always require higher levels of cognitive control and higher attentional resources (see Engle, 2010 on this point). Despite these limits, the evidence here raises questions about the range of possible causes of DD, including the often overlooked visual processing deficit.

This research presents with several aspects of novelty compared to previous research. If the generalised visual impairment hypothesis for DD is correct, then a number of key questions emerge including: (1) what is the critical nature of the visual impairment and (2) why are written words so vulnerable to this impairment? Answering these questions will necessitate further research using a larger sample but the present study indicates that individuals with DD may be impaired on visual, phonological, and visuo-spatial tasks. For this reason, we can speculate that individuals with DD may present with a deficit in the visual as well as in the phonological domain, and that their difficulties in reading may arise as the consequence of these several deficits. As expected, not all individuals with DD showed the same pattern of impairment compared to the TDR group (see Supplementary Materials). These findings confirm that DD is a complex disorder characterised by deficits in different cognitive mechanisms (visual and phonological) that underpin reading. Practitioners working in this field should thus consider assessing a diverse range of abilities rather than limiting their focus to phonological skills, to fully capture the difficulties children may encounter when learning to read.

4 Shallow or deep? The impact of orthographic depth on visual processing in DD

This study is currently under review in Neuropsychologia with the title "Shallow or Deep? The impact of orthographic depth on visual processing in DD"

In this study a comparison between the English and the Italian samples has been made with the aim of clarifying whether any difference characterised DD readers of orthographies with varying orthographic consistency on visual processing tasks. Such comparisons are of crucial importance as they help to elucidate whether even though DD presents with biological similarities, the behavioural manifestation may be influenced by the depth of the orthography.

4.1 Introduction

Developmental dyslexia (DD) is the most common among the specific learning disabilities, affecting up to 15% of the population worldwide (American Psychiatric Association., 2013). Individuals with DD struggle to achieve fluent, accurate reading despite appropriate intelligence and adequate instruction (Zhao, Thiebaut de Schotten, Altarelli, Dubois, & Ramus, 2016). Although most of the research regarding DD has been conducted with children, reading difficulties persist into adulthood (Bruck, 1985; Eloranta et al., 2018; Finucci et al., 1985; Nergård-Nilssen & Hulme, 2014; Shrewsbury, 2016) and their manifestation differs across orthographies, depending on the depth of the writing system (see the orthographic depth hypothesis Frost, Katz, & Bentin, 1987 for further details).

In deep orthographies, in which the mapping between letters and sounds is inconsistent (e.g., English), DD tends to be characterised by slow reading, but in particular by a dramatic impairment in reading accuracy. Conversely, in shallow orthographies, in which the mapping between letters and sounds is generally consistent (e.g., Italian), the prevailing weakness appears to be the ability to achieve automatised reading (Landerl et al., 1997; Spinelli et al., 2005; Wimmer, 1993), leading to slow and effortful decoding of words with accuracy being relatively well preserved (de Jong & van der Leij, 2003; Grigorenko, 2001; Job et al., 1984a; Wimmer, 1993). Despite such differences in the manifestation of DD across orthographies, the commonly accepted explanation for these impairments is a deficit in phonological processing (Snowling, 1981; Swan & Goswami, 1997; Vellutino et al., 2004).

In developmental terms, the phonological deficit is proposed to affect the acquisition of phonological decoding skills (i.e., grapheme to phoneme conversion), which in turn compromises the construction of the orthographic lexicon with repercussions for fluent, whole word recognition and sometimes accurate spelling. The phonological hypothesis explains well the difficulties occurring in deep orthographies but fails to adequately capture the difficulties shown by DD readers of more consistent orthographies, such as Italian, German, and Spanish (e.g., Landerl et al., 1997). An alternative account was proposed by Wimmer (1993) who distinguished between “speed dyslexia”, in which the prevailing phonological deficit manifests in the dysfluent word recognition that characterises DD in shallow orthographies, and “decoding dyslexia”, in which the phonological deficit results in incorrect word decoding, that characterises DD in deep orthographies.

Neuroanatomically, a phonological deficit is often associated with a dysfunction of the left dorsal temporo-parietal region. This is supported by an engagement of the temporo-parietal cortex during normal phonology-based reading (Pugh et al., 2000). Evidence revealed that hypoactivation, particularly in the inferior parietal lobe, characterised individuals with DD in both shallow and deep orthographies (Richlan, 2012). This implies there may be a universal neurocognitive basis for DD, and suggests a core deficit in the phonological domain among individuals with DD, irrespective of orthographic depth (e.g., Goswami, 2002; Paulesu et al., 2001a).

Difficulty with rapid word decoding has rather been associated with a deficit of the left ventral occipito-temporal region, an area involved in whole-word reading (Kronbichler et al., 2008; Price & Devlin, 2011b; Pugh et al., 2000). According to the model of Pugh and colleagues (2000), the dorsal cortex is employed by beginner readers, whereas the ventral cortex is engaged by skilled readers during fast word recognition. Indeed, the development of the ventral circuit would depend on the functionality of the dorsal circuit (Pugh et al., 2000). Hence, a dysfunctional dorsal parieto-temporal cortex could, in turn, lead to a ventral occipito-temporal cortex unoptimised for word recognition, resulting in DD (Pugh, 2006; Pugh et al., 2000; Richlan, 2014).

In contrast with the classical model of Pugh and collaborators, some evidence has shown an early engagement of the left occipito-temporal cortex in non-impaired readers and an early disengagement in DD. In particular, Richlan (Richlan, 2012; Richlan, Kronbichler, & Wimmer, 2011) proposed a model based on a meta-analysis of studies conducted with both children and adults across different orthographies. This model assumes a primary early dysfunction of the occipito-temporal cortex in children with DD, which becomes progressively extended in adulthood. Surprisingly, the results of those meta-analysis also showed a temporo-parietal hypoactivation in the adult studies but not in the child studies (Richlan et al., 2011).

Such results are problematic for the model advanced by Pugh and collaborators (2000) of a primary dysfunction of the dorsal cortex followed by a secondary dysfunction of the ventral cortex in DD. Rather, they suggest a dysfunction of the occipito-temporal cortex is later accompanied by a dysfunction in the temporo-parietal cortex. Although a comparison between the two models is beyond the scope of this study, the findings of Richlan and colleagues underline the importance of the ventral cortex in DD irrespective of age.

Collectively, these findings suggest DD may be underpinned by a core dysfunction in left posterior systems (i.e., dorsal temporo-parietal and ventral occipito-temporal) and thus support the idea of a universal neurocognitive deficit across orthographies (e.g., Paulesu et al., 2001b; Pugh, 2006; Pugh et al., 2000). With respect to the ventral area, neuroimaging meta-analyses of shallow and deep orthographies showed hypoactivation of the left occipito-temporal cortex, including the visual word form area (VWFA), seem to play a universal role in DD irrespective of age or orthographic depth (Martin et al., 2016; Richlan, 2014).

The VWFA is located in the left fusiform gyrus and is hypothesised to be optimised for visual-orthographic word recognition. Specifically, identifying words and letters from lower-level shape images, prior to association with phonology or semantics (Dehaene & Cohen, 2011a; Dehaene et al., 2005; A. Martin, Schurz, Kronbichler, & Richlan, 2015; Richlan et al., 2011). A dysfunction of this area may therefore lead to inefficient reading. Indeed, some individuals with DD present with slow and effortful reading captured by word length effects (i.e., the more the letters in a word, the longer the time needed to read e.g., Martens & de Jong, 2006; Provazza, Giofrè, Adams, & Roberts, 2019; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003; Zoccolotti et al., 2005). This is indicative of the struggle to employ a parallel whole-word and fluid reading strategy. Word length effects have been noted in both children and adults with DD, thus strengthening the account of a dysfunction in the VWFA (e.g., A. Martin et al., 2016; Richlan, 2014; Schurz et al., 2014).

It is important here to consider another influential group of patients from the neuropsychological literature. Lesions to the VWFA often result in an acquired disorder called pure alexia (Dehaene & Cohen, 2011a), characterised by slow and effortful letter-by-letter reading and word length effects. These patients demonstrate simultaneous impairments for stimuli that are as visually demanding as letters/words including abstract visual patterns, objects, and faces (e.g., Behrmann & Plaut, 2014; Roberts et al., 2015, 2013). This pattern of performance has also been noted in individuals with DD (Gabay et al., 2017a; Provazza, Adams, et al., 2019; Sigurdardottir et al., 2018). A recent study from our group (Provazza, Adams, et al., 2019) with highly educated DD individuals showed that their visual impairments were quantitatively related to the extent of reading deficiency, with performance on pattern discrimination tasks decreasing as visual complexity of the stimuli increased.

The key and re-occurring theme emerging from the developmental and acquired literature is that hypoactivation or a lesion to VWFA results in dual reading and non-reading impairments, suggesting a common underlying mechanism – loss of a particular type of visual function, which optimally and rapidly process abstract visual features of stimuli, of which letters are just one exemplar. It can be hypothesised, therefore, that visual difficulties, as well as phonological ones, represent a core deficit in DD irrespective of age and that they cannot be compensated over time.

Despite the accumulating evidence accounting for a pervasive dysfunction of the VWFA in DD, such dysfunction seems to vary according to the depth of the orthography. In particular, research has shown that individuals with DD in shallow orthographies presented with a more consistent hypoactivation in the VWFA compared to individuals with DD in deep orthographies

(Adrián-Ventura et al., 2020; A. Martin et al., 2016; Richlan et al., 2010b). Since the VWFA is engaged in non-orthographic visual processing, it is plausible to assume that a failure in its engagement would result in a common deficit in visual processing in DD regardless of the orthographic depth although this may be more severe in DD in shallow than in deep orthographies.

Based on these assumptions, the aim of the current study was to further investigate the extent to which visual impairments are manifested in DD readers of shallow (Italian) and deep (English) orthographies and thus, whether these represent a core deficit in DD. We compared the performance of two DD samples (Italian, English) with that of two samples of typical developing readers (TDR) matched for age, language and gender. Additionally, in alignment with an account of a universal deficit in the phonological domain in DD, we compared DDs and TDRs on a phonological task.

It was predicted that (1) participants with DD will perform worse than TDRs in the phonological task according to previous evidence of a phonological deficit in DD and will (2) demonstrate impairment in visual tasks, confirming a deficit in processing visual stimuli due to a failure in the engagement of the VWFA; (3) the magnitude of the visual deficit in DD will be greater for the Italian group than the English group, according to the evidence of a more consistent hypoactivation of the VWFA in DD readers of a shallow orthography.

4.2 Method

4.2.1 Participants

Thirty-six university students with DD participated. Italian speakers (N=18) were recruited at the University of Calabria (5 males; age range 19-26; M_{years}= 21.3; SD= 2.34) and British English speakers (N=18) were recruited at Liverpool John Moores University (5 males; age range 19-27; M_{years}= 21.8; SD= 2.29). All participants were in receipt of a formal diagnosis of dyslexia (supplied by a registered assessor of SpLD). Each group of students with DD has been contrasted to a group of typical developing reader (TDR) students. This included 18 Italian speakers recruited at the University of Padova (6 males; age range 19-25; M_{years}=21.17; SD=1.86) and 18 British English speakers recruited at Liverpool John Moores University (7 males; age range 19-28; M_{years}=21.8; SD=2). All groups did not differ for gender, $\chi^2(3) = .70$, $p = .873$, Cramer's $V = .099$, or age, $F(3,68) = .509$, $p = .677$, $\eta^2_p = .022$.

The reading level of English DD and TDR groups was assessed using two reading tasks (i.e., word and nonword reading, see Roberts, Lambon Ralph, & Woollams, 2010). Error rates were not normally distributed, so a Mann Whitney U test was performed. As expected, the TDR group outperformed the DD group in both word ($U = 233.5$, $n = 36$ $p = .02$) and nonword reading ($U = 258.5$, $n = 36$ $p = .002$). The reading level of the Italian DD and TDR groups was also assessed using two reading tasks (word and nonword reading see Cornoldi & Montesano, 2020). Since the error rates were not normally distributed in this group either a Mann Whitney U test was performed. As expected, the TDR group outperformed the DD group in both word ($U = 312$, $n = 36$ $p < .001$) and nonword reading ($U = 242.5$, $n = 36$ $p = .01$). Means and standard deviations for the error rates of the two groups, and group comparisons in terms of Cohen's d, are displayed in Table 4.1.

Table 4.1. Means scores, standard deviations (SD) and effect sizes for the error rates obtained by typical developing readers (TDR) and developmental dyslexics (DD) in the reading tasks

	Italian			English		
	DD	TDR	Cohen's *d*	DD	TDR	Cohen's *d*
Word errors	8.11(6.22)	1.06(1.25)	1.57	6.61(5.27)	3.17(2.89)	.80
Nonword errors	6.67(3.95)	3.39(2.5)	.99	7.50(7.91)	2.00(1.61)	.96

4.2.2 Materials

4.2.2.1 Visual matching tasks (Roberts et al., 2013)

Two visual matching tasks were administered to assess visual abilities and are described below. For each of these tasks, RT and accuracy data were collected.

Checkerboards

A set of 32 black and white checkerboards were used (Figure 5.1). The number of squares in each matrix was either 9 (3×3) or 49 (7×7), forming the visually simple and visually complex sets, respectively. Grids were constructed by avoiding placement of blocks of the same colour together or any other regularity in the patterns (that might simplify visual processing). Stimuli were used to form a triad-based matching-to-sample task, in which the probe was flanked above and below by the target and foil. The position (above/below) of target and foil was randomised. Two types of foil were created: the similar condition reflected foil patterns that differed by only one block from the target pattern; the dissimilar condition reflected foils that differed from the target considerably (by several blocks), such that each foil could be distinguished easily. Three vertically aligned checkerboards appeared on the screen for each trial. The central checkerboard was the probe stimulus, and the participants had to decide whether the top or bottom checkerboard matched the central one (i.e., they had to identify the target), by pressing two different keys on the keyboard ("N" for the stimulus below and "Y" for the stimulus above). Each participant was required to respond as quickly and accurately as possible.

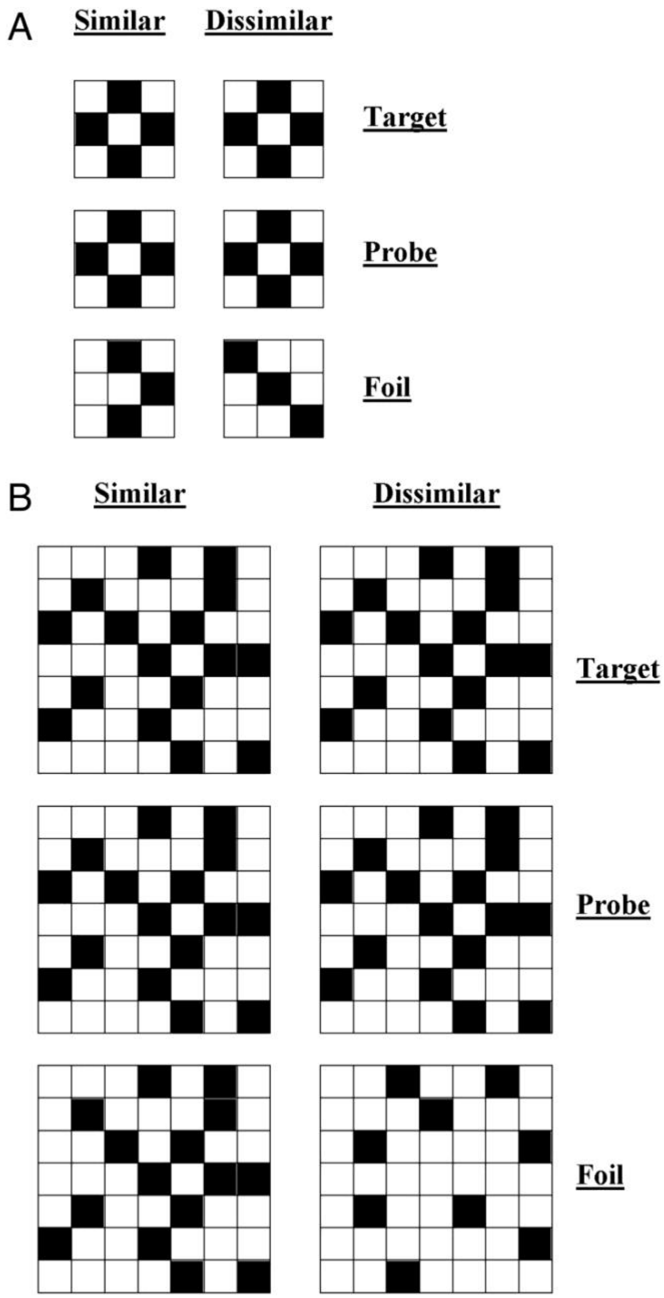

Figure 4.1. Example checkerboard stimuli for (A) visually simple condition and (B) visually complex condition with similar and dissimilar foils (Roberts et al., 2013).

Kanji Characters

A set of 60 single kanji characters were used (Figure 4.2). Visual complexity was defined in terms of the number of strokes in each character. Characters with 2–4 strokes constituted the simple items, and those with 13 strokes formed the complex set. Again, each target character appeared in a matching-to-sample triad. The probe was placed in the centre with the target and foil above or below. The position of the target was randomised across trials. In half the trials, the foil was a character differing only slightly from the target to give the similar condition; in the other half, a character differing from the target considerably was selected for the dissimilar condition. Three vertically aligned Kanji appeared on the screen for each trial. The central Kanji was the probe stimulus, and the participants had to decide whether the top or bottom Kanji matched the central one, by pressing two different keys on the keyboard ("N" for the stimulus below and "Y" for the stimulus above). Each participant was required to respond as quickly and accurately as possible.

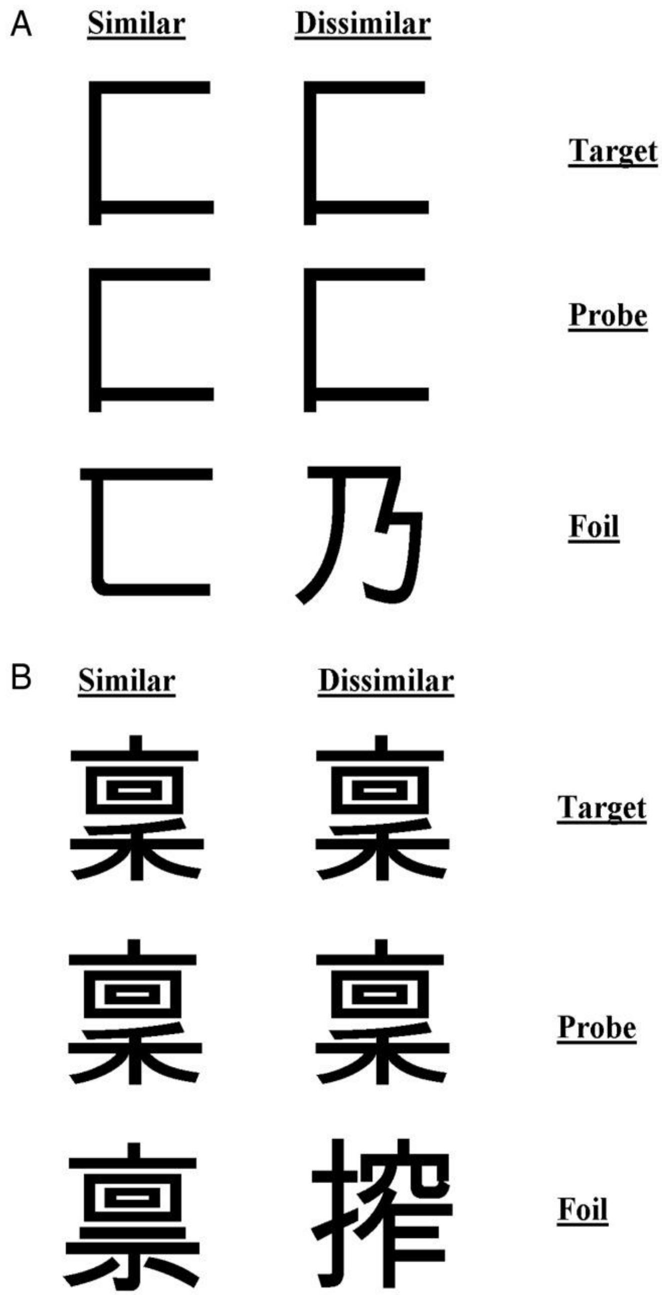

Figure 4.2 . Example kanji stimuli for (A) visually simple condition and (B) visually complex condition with similar and dissimilar foils (Roberts et al., 2013).

4.2.2.2 Phonological tasks (WAIS IV, Wechsler, 2008)

To investigate phonological processing, the digit span test was used. This consists of three subtasks: digit forward, in which participants were instructed to recall as many of the digits as possible in the same order they were presented; digit backward, in which participants had to recall the digits in the reverse order; and digit sequential, which required participants to recall the digits in ascending order of magnitude. The span test score is obtained by summing up the scores in the three span conditions (see Wechsler, 2008 for more detailed information).

4.2.3 Procedure

All the visual matching tasks were administered using E-Prime 2.0 software (MacWhinney et al., 2001). The digit span task was administered by following the instructions included in the administrator manual of the WAIS-IV (Wechsler, 2008). Students were assessed individually in a single session in a quiet room at the institution they attended. The study was approved by the RES Committee North West – Liverpool Central (15/NW/0461), and by the ethics committees of the University of Calabria and the University of Padova and written consent was obtained from all participants.

4.2.4 Statistical analyses

4.2.4.1 Visual processing tasks

Analyses of the visual matching tasks were performed using generalised linear mixed models (GLMM Pinheiro & Bates, 2000) using the “lm4” package (Bates, Mächler, Bolker, & Walker, 2015). GLMM is a robust analysis that allows controlling for the variability of items and subjects, limiting the loss of information due to the prior averaging of the by-item and by-subject analyses (Baayen, Tweedie, & Schreuder, 2002).

In order to obtain the p-values for the random effects, a null model with both random effects was compared with a model in which only one random effect was included. P-values for fixed effects were obtained using the package "car" with the Type II Wald chi-square tests (Fox & Weisberg, 2019). Figures were obtained using the package "ggplot2" (Wickham, 2016).

In each model, participant and trial were identified as random variables, while group (TDR and DD), language (English and Italian), complexity (complex and simple) and similarity (similar and dissimilar) were included as fixed effects. The function "lmer" was used to perform the analyses concerning reaction times (RT), while "glmer" was used to fit the analyses on accuracy. An optimiser was used for the analyses performed fitted with "glmer", i.e., "bobyqa".

4.2.4.2 Phonological task

The analysis of the phonological task was performed using the software SPSS (Version 25, IBM, 2017)

4.3 Results

Means and standard deviations for RT and accuracy of the two groups, and group comparisons in terms of Cohen's d, are displayed in Table 4.2.

Table 4.2. Mean scores, standard deviations (SD) and effect sizes obtained by typical developing readers (TDR) and developmental dyslexics (DD) in all tasks

	Italian			**English**		
	DD	**TDR**	**Cohen's *d***	**DD**	**TDR**	**Cohen's *d***
Visual matching						
Checkerboard RT						
Complex Dissimilar	3504.09(2185.3)	1458.52(573.42)	1.28	1838.35 (535.87)	1417.54(344.42)	0.93
Complex Similar	9694.15(4816.60)	4033.35(1515.452)	1.58	6792.15(2630.16)	5445.70(1530.99)	0.62
Simple Dissimilar	2274.72(696.43)	1122.64(283.54)	2.16	1523.55(407.04)	1207.07(202.48)	0.98
Simple Similar	2837.46(1323.49)	1303.77(348.49)	1.58	1763.09(487.41)	1428.18(249.58)	0.86
Kanji RT						
Complex Dissimilar	1669.79(518.22)	1299.83(282.70)	0.88	2608.4456(889.87)	1932.24(541.32)	0.91
Complex Similar	2608.4456(889.87)	1932.24(541.32)	1.27	1204.08(328.79)	952.65(171.30)	0.95
Simple Dissimilar	1204.08(328.79)	952.65(171.30)	0.76	1912.30(714.05)	1482.72(436.28)	0.72
Simple Similar	1912.30(714.05)	1482.72(436.28)	0.72	1838.35 (535.87)	1417.54(344.42)	0.93
Checkerboard accuracy						
Complex Dissimilar	0.99(0.03)	0.98(0.03)	0.33	0.98(0.03)	1.00(0.01)	0.89
Complex Similar	0.93(0.10)	0.84(0.15)	0.70	0.87(0.13)	0.91(0.11)	0.33
Simple Dissimilar	0.99(0.02)	0.99(0.02)	0	0.99(0.02)	0.99(0.04)	0
Simple Similar	0.98(0.03)	0.95(0.06)	0.63	0.95(0.07)	0.96(0.05)	0.16

Kanji accuracy						
Complex Dissimilar	0.99(0.02)	0.97(0.04)	0.63	0.98(0.03)	0.98(0.03)	0
Complex Similar	0.97(0.06)	0.93(0.08)	0.56	0.91(0.10)	0.97(0.03)	0.81
Simple Dissimilar	0.99(0.02)	0.99(0.03)	0	0.99(0.02)	0.99(0.03)	0
Simple Similar	0.95(0.08)	0.96(0.05)	0.14	0.95(0.05)	0.94(0.05)	0.2
Phonology						
Digit Span	21.00(3.8)	31.00(5.8)	2.03	24.22(4.5)	31.61(4.3)	1.67

4.3.1 Reaction times

4.3.1.1 Checkerboard

Random effects were statistically significant ($p < .001$). All fixed effects are presented in Table 4.3 (Model 1). The four-way interaction between group, language, visual complexity, and visual similarity was statistically significant, $\chi^2(1) = 14.38$, $p < .001$. Figure 4.1 shows that participants in the TDR group in the two languages performed similarly, outperforming participants with DD, who in general presented with slower RT. Intriguingly, some differences emerged in the complex similar condition, which was the most visually challenging condition. In this condition, RTs were generally higher and DD Italian participants performed poorly compared with all the other groups, including DD English participants.

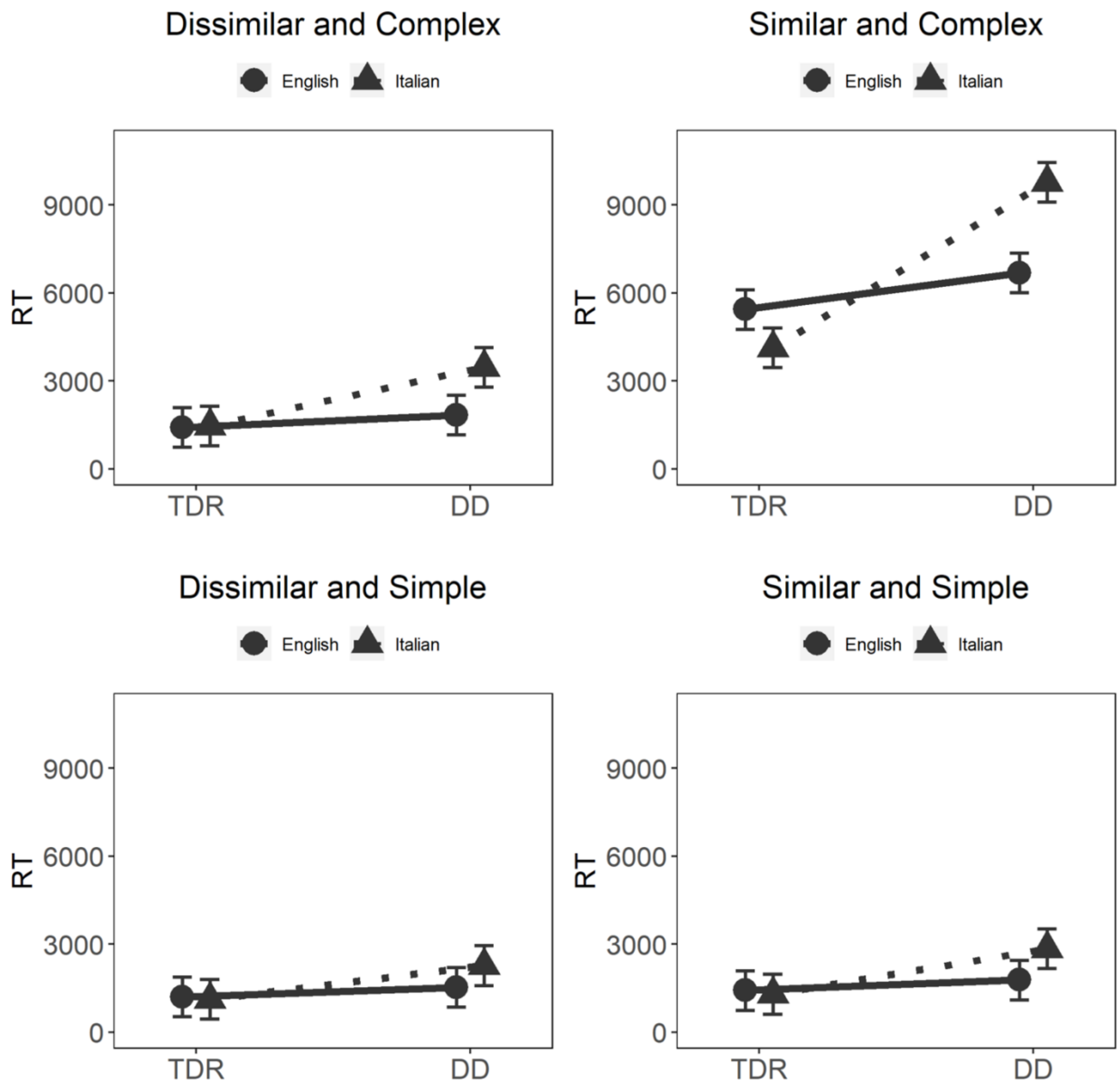

Figure 4.3. Checkerboard results. TDR= typical developing readers, DD = developmental dyslexics, RT = reaction times.

4.3.1.2 Kanji

Random effects were statistically significant ($p < .001$). All fixed effects are presented in Table 4.3 (Model 2). The four-way interaction as well as three out of four of the three-way interactions were not statistically significant. However, the interaction between group, language, and visual similarity was statistically significant, $\chi^2(1) = 27.62$, $p < .001$. Figure 4.2 shows that participants in the TDR group in the two languages performed similarly, outperforming participants with DD, who in general presented with slower RTs. Intriguingly, some differences emerged in the visually challenging similar condition. In this condition, RTs were generally higher and DD Italian participants performed quite poorly as compared with all the other groups, including DD English participants.

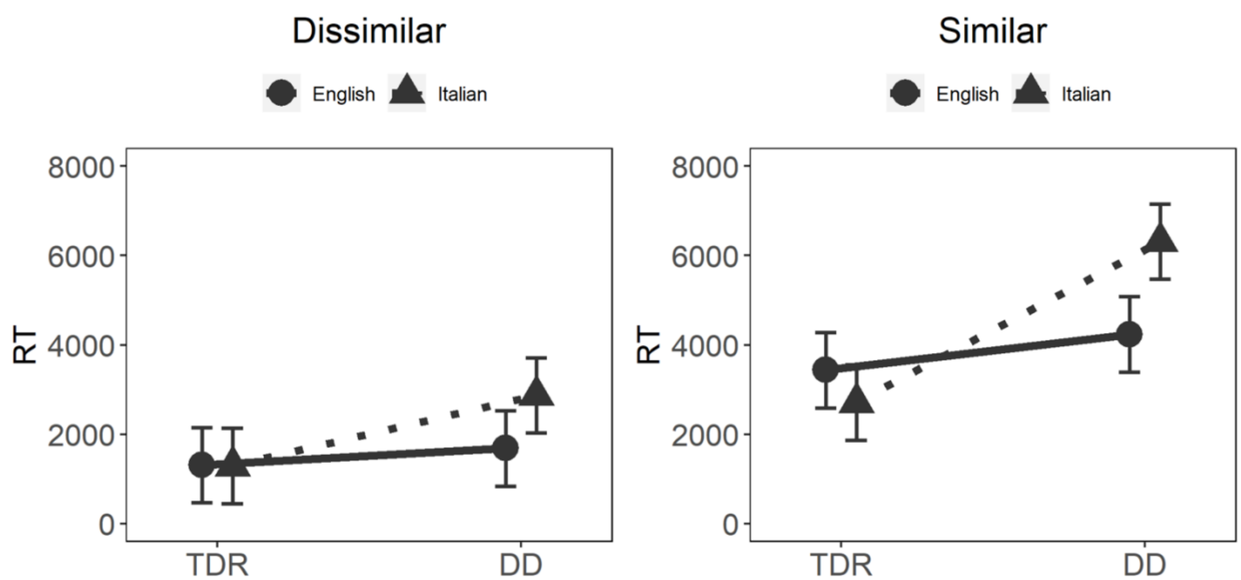

Figure 4.4. Kanji results. TDR = typical developing readers, DD = developmental dyslexics, RT = reaction times.

4.3.2 Accuracy

4.3.2.1 Checkerboard

Random effects were statistically significant ($p < .001$). All fixed effects are presented in Table 4.3 (Model 3). The four-way as well as all the three-way interactions were not statistically significant. As for the two-way interactions, only the interaction between complexity and similarity was statistically significant (Table 3). Figure 4.3 shows that the complex similar condition was the most difficult, with higher error rates.

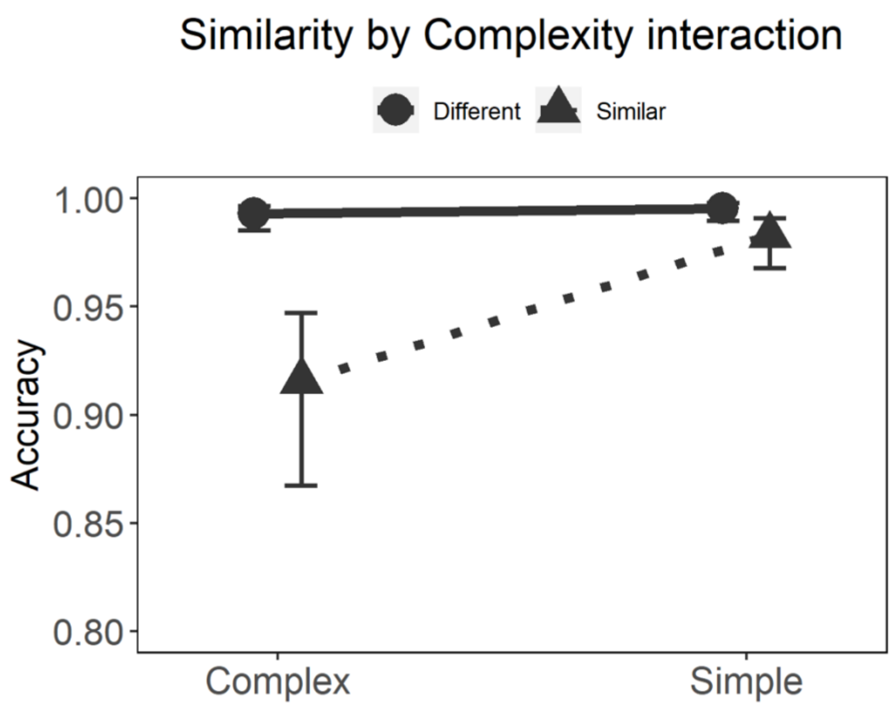

Figure 4.5. Similarity x complexity interaction in the Checkerboards accuracy rate

4.3.2.2 Kanji

Random effects were statistically significant ($p < .001$). All fixed effects are presented in Table 4.3 (Model 4). All four-way interactions were not statistically significant. As for the three-way interactions, only the interaction between group, language and complexity was statistically significant (Table 3). Figure 4.4 shows that in the complex condition DD English participants had a somewhat lower accuracy, .973, with 95% CIs [.948, .985], however inspection of the confidence intervals showed that this performance is highly overlapping with the performance of English TDR, .988, with 95% CIs [.976, .994]. These results taken together indicate that the overall performance was extremely high and that participants made very few errors.

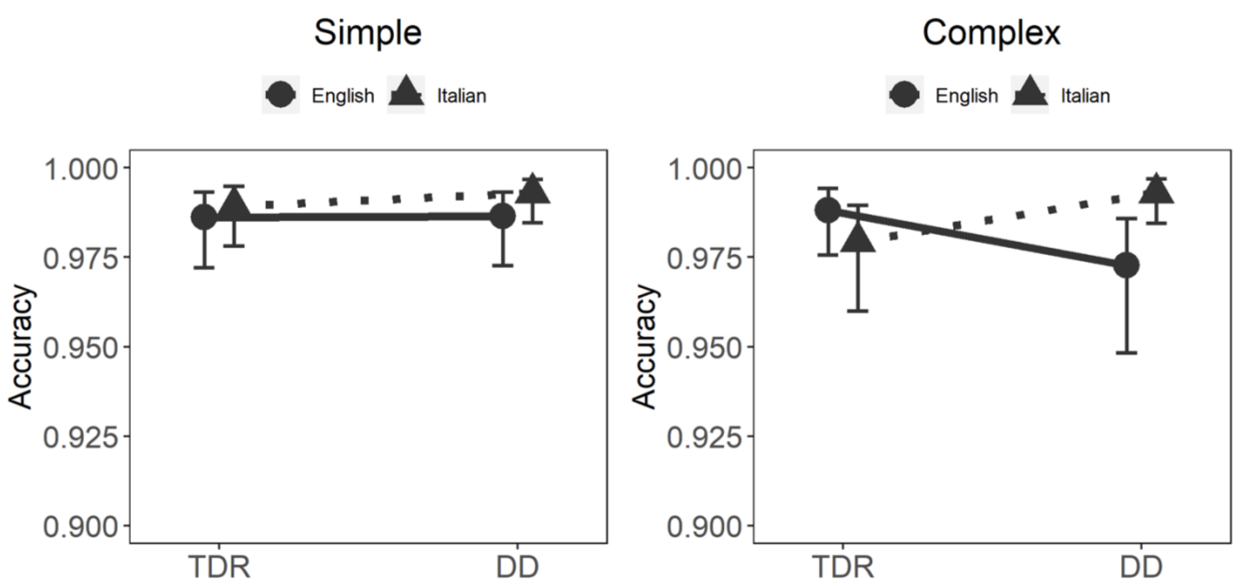

Figure 4.6. Kanji results on accuracy. TDR = typical developing readers, DD = developmental dyslexics.

Table 4.3. List of fixed effects

	Model 1		Model 2		Model 3		Model 4	
	$\chi^2(1)$	p	$\chi^2(1)$	p	$\chi^2(1)$	p	$\chi^2(1)$	p
Group	**31.35**	**.000**	**39.01**	**.000**	0.66	.418	0.21	.645
Language	**4.98**	**.026**	**8.16**	**.004**	0.11	.741	1.88	.170
Complexity	**270.05**	**.000**	**27.13**	**.000**	**16.39**	**.000**	3.04	.081
Similarity	**228.09**	**.000**	**64.53**	**.000**	**37.81**	**.000**	**44.50**	**.000**
Group*Language	**12.48**	**.000**	**12.98**	**.000**	**9.06**	**.003**	**3.80**	**.051**
Group*Complexity	**82.71**	**.000**	**23.72**	**.000**	0.64	.423	0.68	.410
Language*Complexity	**8.21**	**.004**	2.04	.153	2.24	.134	0.20	.655
Group*Similarity	**56.55**	**.000**	**78.50**	**.000**	1.39	.238	2.29	.131
Language*Similarity	0.33	.563	**5.21**	**.022**	1.20	.274	0.51	.476
Complexity*Similarity	**173.02**	**.000**	0.36	.549	**3.84**	**.050**	0.33	.568
Group*Language*Complexity	**36.95**	**.000**	3.46	.063	0.04	.842	**8.51**	**.004**
Group*Language*Similarity	**23.85**	**.000**	**27.62**	**.000**	0.29	.587	0.06	.806
Group*Complexity*Similarity	**38.15**	**.000**	0.03	.873	0.63	.429	1.91	.167
Language*Complexity*Similarity	0.07	.788	0.02	.887	0.01	.927	0.04	.845
Group*Language*Complexity*Similarity	**14.38**	**.000**	0.89	.345	1.10	.295	0.06	.802

Note. .000 means 0 when rounded to the third decimal place. Bold denotes statistical significance.

4.3.2.3 Phonological processing

ANOVA was conducted to compare the performances of the four groups (Figure 4.5). The results showed that the DD group performed worse than TDR group, $F(1,68) = 62.46$, $p < .001$, $\eta^2_p = .480$, with a large effect size regardless of the language $F(1,68) = 3.03$, $p < .086$, $\eta^2_p = .043$. The interaction Group × Language was not statistically significant $F(1,68) = 1.41$, $p = .240$, $\eta^2_p = .020$ with a small effect size, indicating that there was not a statistically significant difference in terms of phonological processing between the DD groups in the two languages.

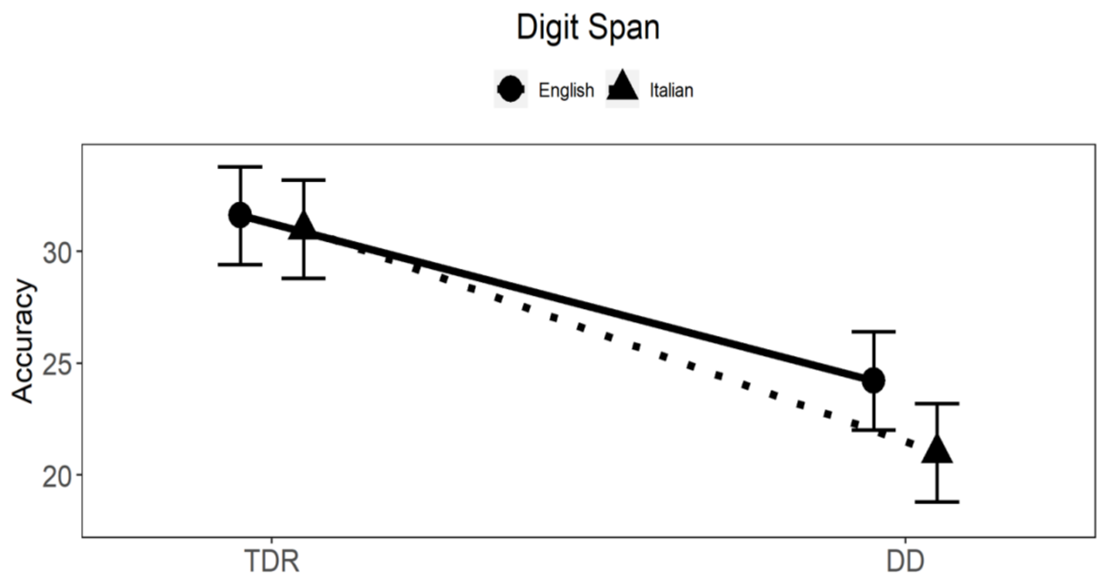

Figure 4.7. Group performance in the phonological task. TDR = typical developing readers, DD = developmental dyslexics.

4.4 Discussion

The aim of this study was two-fold. First, to evaluate the presence of an impairment in the phonological domain in adults with DD in shallow and deep orthographies, in accordance with the phonological deficit hypothesis. Second, and more importantly, to investigate whether and to what extent an impairment in the visual domain could characterise DD across these different orthographies.

The results demonstrate that participants with DD were impaired in the phonological task, regardless of orthography. Both DD groups performed significantly worse on the span test, with a large effect size, compared to the TDR groups. These findings were expected and confirm previous evidence highlighting impaired performance in DD compared to controls on phonological tasks and the critical role played by phonology in reading acquisition (Carroll & Snowling, 2004; Goswami & Bryant, 2016; Paulesu, 2001; Snowling, 1981; Swan & Goswami, 1997). In addition, participants with DD in both shallow and deep orthographies also presented with a deficit in processing visual stimuli, presumably due to VWFA dysfunction. These results align with previous research conducted with acquired dyslexic patients (i.e., patients with pure alexia see Roberts et al., 2013).

To reiterate, pure alexia is characterised by slow and effortful letter-by-letter reading and visual processing impairments due to damage in the VWFA (Roberts et al., 2015, 2013). Since both DD groups performed worse than TDRs in the visual matching tasks, this confirms the presence of a deficit in visual processing, which may also be explained by a dysfunction of the VWFA. Notably, this deficit was evident in RT, whereas no difference in the accuracy rates was found. This highlights the importance of considering speed of processing when visual aspects are evaluated in DD since these can easily be missed if only accuracy is measured (Provazza, Adams, et al., 2019).

Collectively, these findings confirm the universality of the impairments in DD regardless of the orthography and that a dysfunction in both the dorsal and the ventral areas seems to characterise DD in deep and shallow orthographies (Paulesu et al., 2001b; Pugh, 2006). Moreover, the impairment in processing visual material shown by participants with DD in comparison to TDRs in both orthographies confirms that DD is a heterogeneous disorder in which a deficit in both the phonological and the visual domains plays a role in its manifestation.

As predicted, the extent to which visual processing was impaired in the DD groups varied depending on the orthographic depth. The Italian DD group performed significantly worse than the English DD group in the visual matching tasks. These differences were particularly evident in the complex and similar conditions, where the performance of the Italian DDs was poorer compared with all the other groups, including the English participants with DD. These results suggest that, despite a common hypoactivation of the VWFA in DD across orthographies, the degree of this hypoactivation might vary in shallow and deep orthographies and this variation might be accounted for by the consistency of the writing system.

According to the psycholinguistic grain size theory (Ziegler & Goswami, 2005), readers of shallow orthographies tend to rely more on small grain sizes when reading (although a whole word reading strategy is still employed by readers of transparent orthographies see Marinelli et al., 2016 for further details), whereas readers of deep orthographies may rely more heavily upon larger grain sizes, which may be more reliable in a more inconsistent writing system. It has been found that the VWFA is engaged not only in a whole word recognition strategy but also in decoding processing. Therefore, a primary deficit in reading speed shown by DD in shallow orthographies could be due to a more consistent hypoactivation of the VWFA, which in turn determines a failure of an efficient lexical and sub-lexical process in DD in such orthographies (Richlan et al., 2010b; Wimmer et al., 2010). Moreover, since the VWFA is not only assigned to process letter strings but is also activated in tasks that require the processing of different visual stimuli (Price & Devlin, 2003, 2011a), this primary dysfunction in the VWFA in DD may also account for the results we obtained in this study, in which DDs were severely impaired in visual processing compared to TDRs.

To summarise, this study aimed to investigate phonological and visual processing in adults with DD reading in a shallow and a deep orthography, with the objective of clarifying the extent to which a deficit in phonology and visual processing might differently contribute to the manifestation of DD across orthographies varying in orthographic depth. The results confirmed that a phonological deficit plays a similar role in DD regardless of the opacity of the writing system. More intriguingly, the role of visual processing seems to be modulated by orthographic depth. In particular, DD readers of a shallow orthography (Italian) were more impaired in processing visual stimuli than DD readers of a deep orthography (English).

It is worth noting the small sample size may represent a limitation in this study. However, the analytic approach employed (i.e., generalised linear mixed models) in the tasks that required more complex analyses strengthened the experimental power of the by-subject and by-item analyses and limited the loss of information due to the prior averaging of the by-subject and by-item analyses (Baayen et al., 2002; Paizi et al., 2013). Finally, it is worth noting that this research has been conducted with adults with DD. It would be of particular interest to investigate the same aspects in a population of young people to understand whether the same impairments in visual and phonological processing would also characterise children with DD or if the role of vision and phonology would be different in this population. Despite these limitations, the results of this study provide insight into the role of visual and phonological impairments in participants with DD across orthographies.

To conclude, these findings highlight the crucial importance of the visual domain in reading and show how a deficit in this domain can be a critical feature in DD, particularly in shallow orthographies. Given that most of the evidence relating to DD has been conducted with participants reading an English orthography, such cross-linguistic evidence is of particular importance. English is in fact an “outlier” orthography and thus, one might question whether it is possible to generalise findings based on this outlier language to more consistent orthographies or if they are rather biased by such “anglocentricity” (Share, 2008a).

The similarities, but especially differences in DD highlighted in this research may have important clinical implications for identification, assessment, and intervention in this population. Indeed, the results might be of great importance for the clinical assessment of DD across orthographies with a different degree of depth. Clinicians working with DD populations should be aware that DD is a complex disorder characterised by various deficits (i.e., visual and phonological) and that the extent to which these deficits are critical in DD may depend on the consistency of the writing system.

5. General Discussion

5.1. Chapter overview

The General Discussion is divided into three main sections. The first section summarises the main findings of the research. In the second section, evaluation of theoretical and clinical implications are provided and in the third section, the direction of future research is outlined.

5.2. Summary of findings

Overall, the aims of the thesis were 1) to explore the contention that the phonological deficit hypothesis is not sufficient to account for poor reading in DD and that therefore the interplay of other cognitive components, such as visual processing would better accommodate DD profiles and 2) to examine the impact of visual processing deficit on fluent reading in languages with different orthographic systems, since it may vary according to transparency of the orthography itself. These questions were driven by the primary systems framework of generic, rather than reading-specific systems underpinning reading.

In Study 1 (Chapter 2), WLEs in reading were investigated in a group of English university students with DD. Although such effects, proposed to reflect the serial processing of small individual units (letters) have been identified in DDs reading a transparent orthography, the evidence for a WLE in adult DDs reading an opaque orthography, is scant. The results confirmed previous findings of WLEs in transparent orthographies also strongly affecting reading in the DD group reading an opaque orthography, whereas in the TDR group no WLE was detected. Interestingly, contrasting effects were observed for reading rate and accuracy. The conclusion that WLEs in DD seem to be independent of the transparency of the orthography, speaks to the question of whether this phenomenon - which in developmental terms could relate to a failure to achieve automaticity with larger grain sizes - might be better explained as reflecting damage to the visual apex of the triangle model as previously observed in patients with pure alexia. Such evidence therefore prompted the investigation set up in Study 2 (Chapter 3), where visual processing in individuals with DD was investigated.

In Study 2 (Chapter 3), a broad battery of assessment was employed with the aim to comprehensively assess the performance of English DDs in visual processing, visuo-spatial and phonological tasks. The results from Study 1 of a strong WLE in the DD group led to the hypothesis that such individuals might be impaired in processing visually demanding stimuli more generally, of which letters and words are just a particular exemplar. Thus, visual impairment might be therefore expected to also affect performance in VSWM tasks. The results obtained in Study 2 revealed that the DD group performed worse than TDRs in the phonological task, replicating evidence of the impact of phonology in reading disorders. More intriguingly, the DD group also performed worse than TDRs in visual processing and VSWM tasks. This evidence is consistent with the notion of domain generality postulated by the primary systems hypothesis and suggests that the phonological deficit hypothesis *per se* may not be sufficient to account for the range of difficulties experienced by those who are reading impaired. It is worth noting the causal influence of the VSWM deficits and slower visual matching identified in DD on the development of reading deficits cannot be clearly established. Therefore, further research would help to clarify whether visual processing and VSWM play a casual role in DD or they may be a co-occurring symptom that do not have a direct influence on the development of reading deficits (see the next section for further discussion on the issue).

Another source of explanation for VSWM difficulties in DD can be attributed to a deficit of the central executive which could account for both phonological and visuo-spatial impairments in participants with DD (Palmer, 2000; Smith-Spark & Fisk, 2007). However, other research has found mixed evidence of impaired central executive in DD compared to controls (Jeffries & Everatt, 2004; Kibby, Marks, Morgan, & Long, 2004) with these authors also finding deficits only in the phonological loop and not in visuo-spatial working memory. It therefore might be that individuals with DD suffer from a deficit at the level of the central executive as observed in impairments in tasks that require more attentional resources (see Arrington et al., 2014; Smith-Park, Frisk, Fawcett & Nicolson, 2003) as indeed was found in this thesis as well (i.e., sequential matrices see Study 2 Chapter 3). However, in contrast to Jeffries and Everatt, (2004) and Kibby, Marks, Morgan, and Long, (2004) the current DD sample also struggled with visuo-spatial working memory. Moreover, these deficits were identified in VSWM tasks in which the attentional control requirement was lower, for example simultaneous matrices and balloons. It might therefore be postulated that, at least in the DD individuals participating in the current studies, that VSWM difficulties may not only be due to deficient central executive processes but may be considered as a consequence of visual processing deficits which in turn may have led to impaired performance in VSWM.

As for the visual processing deficits shown by participants with DD in both languages, they might arguably be attributed to deficiencies in executive functioning, most likely a deficit in inhibiting irrelevant information (Brosnan et al., 2002). Brosnan et al. (2002), concluded that individuals with DD have deficiencies in executive functions relating to inhibition of distractors and to sequencing of events. However, participants with DD contributing to the studies presented in this thesis did not show any difference in accuracy compared to controls in the visual matching tasks (Kanji and Checkerboards). In fact, DDs demonstrated comparable accuracy in those tasks, with the principal deficit being that they were considerably slower than their matched controls.

This pattern is consistent with the data from patients with pure alexia (Roberts et al., 2013) and seems to indicate low-level, slow processing of visual information more so than a deficit in generic high-level cognitive processes. As previously highlighted, individuals with DD have been shown to be impaired in rapidly naming familiar objects, that is a RAN deficit (Fawcett & Nicolson, 1994; Norton & Wolf, 2012; Swanson et al., 2003; Wolf & Obregón, 1992). Even though some ambiguity remains in accounting for the evidence of the cognitive skills measured by RAN (see introduction in this thesis where the issue has been discussed), one convincing hypothesis suggests deficits in RAN can be accounted for by underlying visual processing impairments (Stainthorp et al., 2010). Such an account is in line with the visual processing deficit found in participants with DD in this thesis.

However, given such slowed performance when processing visual stimuli observed in participants with DD in both languages studied here, one may hypothesize it is due to a wider and more generalised processing speed deficit. Individuals with DD have been observed to present with slow performance in tasks other than visual ones (see e.g., Stoodley, & Stein, 2006 for evidence on slow motor performance in participants with DD). It is worth noting though that individuals with DD only performed worse than controls in the more complex conditions, with no significant differences found in the simple conditions of both tasks suggesting some influence of processing complexity. This again align with the results found in the study with patients with pure alexia in which the authors suggested that the patients' non-orthographic recognition impairments reflected deficit in processing complex visual information (Roberts et al., 2013).

Furthermore, a cross linguistic investigation of processing speed in DD, low-IQ and typically developed participants reading of a transparent (Italian) and opaque (English) orthography found that only individuals with low-IQ performed poor in processing speed tasks (i.e., higher RTs).

Intriguingly, participants with DD did not differ significantly from controls in processing speed. The authors concluded that DD is a reading disorder that arise in the context of normal IQ and speed processing (Bonifacci & Snowling, 2008).

Therefore, the findings presented in this thesis can be linked to specific visual processing deficit. Noteworthy, given the novelty of the investigation presented in this thesis and especially since VSWM is not commonly investigated in DD, further research is needed to replicate the results presented here and to confirm the conclusions drawn.

In Study 3 (Chapter 4) two groups of individuals with DD reading in Italian and in English, were compared in the visual and the phonological tasks, with the view to investigate the extent to which visual processing might be differently impaired in DD in different orthographies. Intriguingly, the results of the comparison showed that the Italian DD sample was significantly more impaired than the English DD sample in processing visual stimuli. This evidence was explained as a possible greater hypoactivation of the VWFA in Italian poor readers. VWFA indeed has been shown to be involved in both reading and non-reading visual processing. These findings therefore offer a novel account of the debate of the role played by visual processing in DD as well as informing our understanding of the universal manifestation of DD across orthographies varying in consistency.

5.3 Theoretical and clinical implications

The findings presented in this thesis demonstrate that DD may not always reflect solely the result of impaired phonological processing but may be better explained in terms of a dual phonology-visual processing deficit, both of which can be more or less critical, depending on the orthography in question. Despite its importance in reading development, the phonological deficit hypothesis may not always be a sufficient account to explain poor reading performance in DD. For instance, previous literature has demonstrated that individuals with DD do not always present with phonological deficits (Bosse et al., 2007a; Giofrè, Toffalini, Provazza, Calcagni, et al., 2019). Moreover, not all those children who have poor phonological skills present as DD (Elliot & Grigorenko, 2014; Gibbs & Elliott, 2020).

A deficit in the visual domain has been suggested to affect individuals with DD in previous literature, albeit with some limitations. The magnocellular deficit hypothesis, for instance, seems to account for impairment in phonological dyslexia but struggles to explain poor reading performance in individuals with surface dyslexia, in which the main characteristic is poor word recognition (Coltheart et al., 1983; Job et al., 1984b; Zabell & Everatt, 2002; Zoccolotti et al., 1999c). Moreover, it is not clear how the magnocellular hypothesis explains reading difficulties in DD over and above phonological processing (see Elliot & Grigorenko, 2014 for a review). The visual attention span deficit on the other hand, accounts for impaired reading only in the surface dyslexia subgroup, in terms of narrow visual attention span, whereas phonological dyslexia is considered as the result of impaired phonological processing (Bosse et al., 2007a). The aim of this thesis was to investigate visual processing in DD without recourse to distinguishing these two subgroups. In fact, such a distinction is typically employed within the DRC model, which accounts for reading impairments in DD but struggles to support non reading deficit.

A very different approach to the explanation of DD is the primary systems hypothesis (Hoffman et al., 2015; Patterson & Lambon Ralph, 1999; Woollams, 2014b), which suggests that reading abilities are underpinned by three primary non-task specific systems. In this configuration, reading is accomplished by three general systems of vision (orthography), phonology and semantics. This view is closely tied to the "triangle" model of reading (Plaut et al., 1996) and it explicitly predicts that the reading deficit will be accompanied by other perceptual, non-verbal difficulties. The results of this thesis fit within the primary systems approach to reading, usually employed in the context of acquired dyslexia (Roberts et al., 2015, 2013; Woollams, 2014b; Woollams et al., 2014) but extends this to the investigation of the development of reading skills, and therefore represents an aspect of novelty (although see Sotiropoulos & Hanley, 2017).

Within the primary systems view, reading and non-reading impairments are explained in terms of damage to one of the primary systems (see Patterson & Lambon Ralph, 1999; Woollams, 2014b). As shown in the studies presented in this thesis, participants with DD performed worse than their matched controls in both non-reading phonological *and* visual tasks. In terms of primary systems, this evidence speaks for a deficit in both the phonological and the visual systems of the triangle model. This has important theoretical implications. It shows that DD should be considered a broad terminology, in which both phonological and visual impairments may play an important role in causing poor reading (Giofrè, Toffalini, Provazza, Calcagni, et al., 2019). Additionally, the comparison between English and Italian DD samples showed that both were impaired in processing visually demanding tasks thus strengthening the contention of visual processing as pivotal in DD, irrespective of orthographic consistency. More intriguingly, the Italian sample was more impaired than the English sample in visual tasks. A possible explanation for this is that the VWFA, which is implicated in word recognition as well as in processing visual stimuli, might be more hypoactivated in DD reading of a transparent language.

At a neural level, the VWFA is activated in whole word recognition as well as in the analysis of single letters, letter features, and in non-reading visual tasks (Price & Devlin, 2011a). Additionally, increased activation is observed during processing of unfamiliar stimuli for non-reading (e.g., face and object recognition, pattern discrimination) and reading tasks (e.g., low frequency words and nonwords). Hence, greater activation of the VWFA was expected during processing of unfamiliar visual stimuli in the visual matching tasks. The difficulties shown by both DD samples, but in particular by the Italian DD sample in processing unfamiliar visual stimuli, indicated that a visual processing deficit may impact more severely DD in transparent rather than in opaque languages. This may therefore indicate that the contribution of the VWFA in transparent orthographies, such as Italian, is increased since readers of transparent orthographies rely to a greater extent on serial decoding, or, in terms of grain size theory, on smaller grain sizes when reading (Ziegler & Goswami, 2005). As previously underlined, the grain size hypothesis postulates that readers of transparent orthographies rely heavily on smaller units (grain sizes) when reading due to the specific characteristic of their orthographic system. This is especially true for unfamiliar words, such as low frequency words and nonwords. Readers of opaque orthographies, on the other hand, employ larger grain sizes to access reading due to the inconsistency (i.e., opacity) of the orthographic system (Ziegler & Goswami, 2005).

Evidence of hyperactivation of the VWFA in reading of unfamiliar words came from an fMRI study conducted in a population of readers in a transparent language (i.e., German) in which a sample of DDs and a sample of non-impaired readers read a list of words and pseudowords (Schurz et al., 2010). The non-impaired readers showed a length by lexicality interaction in the VWFA (i.e., greater hypoactivation of the VWFA with increments in the letters in the pseudowords but not for words), however, the DD sample failed to show the same interaction, presenting with prolonged response latency in each condition (Wimmer et al., 2010). This evidence suggests a failure of the DD sample in activating the VWFA to employ a whole word recognition strategy. More importantly, they did not show increased activation of the VWFA in response to unfamiliar stimuli (i.e., pseudowords). Such evidence is confirmed in this thesis, in which the Italian DD sample performed worse than the other samples in processing unfamiliar visual stimuli and speaks in favour of a failure in the activation of the VWFA.

As for the English DD sample, they also presented with impaired visual processing, however their performance was less compromised than that of the Italian sample. Such a result may indicate that, although visual processing is a predictor of DD across different orthographies, it might have a greater impact in transparent orthographies due to the characteristic of the orthography. In opaque orthographies such as English, a greater reliance upon orthographic knowledge (larger units such as whole words) is a determinant for mastery reading due to the nature of the orthography itself. Consequently, an early acquisition of a parallel reading strategy (larger grain size employment), may be essential in a less transparent orthography, but it is less important in a transparent orthography such as Italian, due to the consistency of the speech sound mapping (see e.g., Marinelli et al., 2016). This, in turn leads to a reduced reliance on the VWFA in English compared to transparent orthographies such as Italian.

In terms of a primary systems approach and the triangle model specifically, both the English and Italian DD samples showed a deficit in the visual and phonological systems even though the visual system seems to be more impaired in the Italian sample than in the English sample. The study on WLE conducted in the English sample and presented in Chapter 2, confirms this. The DD sample presented with a strong WLE in each condition considered (i.e., familiar words, unfamiliar words and nonwords), thus showing a possible hypoactivation of the VWFA. This result mirrored the study conducted with a German DD sample which presented with WLE in both word and nonword reading (Wimmer et al., 2010). Intriguingly, the TDR sample did not show any WLE in nonword reading, which contrasts with the findings of Wimmer and collaborators (2010) with the

German sample. Such a result indicates that in an opaque orthography such as English, in which the employment of smaller grain sizes might result in a higher error rate, the VWFA plays a less important role compared to other brain areas.

Evidence of orthography-specific brain hypoactivation in transparent vs opaque orthographies was found in a meta-analysis conducted on functional studies in DD readers of transparent and opaque orthographies (Martin et al., 2016). Individuals with DD in both orthographies presented with a strong hypoactivation of the left occipitotemporal cortex, including the area usually identified as VWFA (Dehaene & Cohen, 2011a). However, the extent of such hypoactivation varied according to the opacity of the orthographic system, and it was higher in transparent orthographies. With respect to DD in opaque orthographies, the higher convergence of hypoactivation was found in the inferior frontal gyrus, pars triangularis. This area is implicated in phonological and semantic reading processes (Price, 2012) and might therefore explain poor reading in DD in opaque orthographies, in terms of lexico-semantic and phonological reading difficulties. Hypoactivation of the inferior frontal gyrus was also identified in the brain of DD individuals reading of transparent orthographies, however with higher convergence of hypoactivation in the pars orbitalis and in the left frontal operculum (Martin et al., 2016).

These findings speak in favour of a universal neurocognitive basis of DD (Paulesu et al., 2001a) which would lead to deficit in both the phonological and the visual domain albeit with additional orthography-specific variations. Interestingly, such evidence of orthographic-based differences in DD seems to be replicated, to a behavioural level, by the results presented in this thesis.

The results discussed so far have not only theoretical but also clinical implications. First, the presence of impaired visual processing in DD needs to be taken into account when assessing individuals with DD and especially children for whom an early identification of phonological and visual processing deficit would be beneficial in terms of efficacy of potential treatment. Assessing visual processing skills along with phonology, would help practitioners working in the field of reading difficulties to construct a better profile of the individual and therefore increase the potential to provide a more effective treatment. In fact, assessing only phonology might be misleading and lead the practitioners to miss some information about the individual which can be important for the implementation of the treatment, especially in those orthographies in which visual processing seems to impact more on reading acquisition and poor reading. Also, given that not all individuals who struggle to read present with phonological impairments (see e.g., Bosse et al., 2007b; Elliot & Grigorenko, 2014), a screening of their visual processing skills may be crucial for the efficacy of the intervention.

Evidence of the important role of visual processing in DD and especially of the assessment of visual processing in DD has been recently confirmed (Rauschenberger, Baeza-Yates, & Rello, 2020; Rauschenberger, Rello, Baeza-Yates, & Bigham, 2018). In this work, the authors presented an approach for universal screening of DD using machine learning models with data gathered from a web-based language-independent game, called *MusVis*. The game encompasses visual and auditory elements and was designed taking into consideration the analysis of mistakes people with DD generally make (e.g., for the visual part, the stimuli were designed to share similar features as well as present with horizontal and vertical symmetries which are difficult to be processed by individuals with DD see Rauschenberger et al., 2018). The study was conducted with 313 children (116 with DD) speaking German and Spanish and trained predictive machine learning models with the collected data.

The rationale beyond the study was the claim that DD represent more a spectrum than a discrete term and therefore different aspects, over and above phonological processing, may cause reading disabilities (Elliot & Grigorenko, 2014; Gibbs & Elliott, 2020; see Rauschenberger et al., 2020). In addition, even though some examples of software for the screening of DD already exist (e.g., Dytective see Rello et al., 2016) they are, on one hand, language-based tools which necessitate being adapted to different languages and therefore cannot be universally used for the screening of DD. On the other hand, they require some specific linguistic knowledge such as speech to sound mapping that is not accessible prior to reading (Rauschenberger et al., 2018). Therefore, the implementation of a language-independent software may facilitate the screening of DD in different languages as well as its implementation with preschool children (Rauschenberger et al., 2020, 2018).

The results showed that the predictive learning models yielded an accuracy of 0.74 for German and 0.69 for Spanish in simulating the performance of DD as well as a F1-score of 0.75 for German and 0.75 for Spanish. Such evidence, however preliminary, suggests that non-linguistic aspects, such as visual processing, are impaired in DD. Additionally, being the instrument employed in this study independent from reading achievement, it can be used to assess children at risk of developing reading difficulties before they access formal education, and thereby facilitating early intervention, which in turn would positively affect reading acquisition (Rauschenberger et al., 2020). Furthermore, a language independent screening task of DD is undoubtedly advantageous, given that it is suitable for administration in different languages. Finally, this study is in line with the evidence presented in this thesis, which demonstrates that DD is as an umbrella term in which not only phonological processing, but also other cognitive components such as visual processing are impaired in poor readers.

6.4. Direction for future research

This thesis has provided some critical insights into the role of visual processing in DD and its contribution in poor reading across orthographies. Below, some future directions are highlighted, which, if further explored, may help to increase our understanding of DD.

As already discussed, in Study 3 (Chapter 4) the visual impairment in the two DD groups was explained in terms of hypoactivation of the VWFA, which seems to be greater in transparent than in opaque orthographies (see Martin et al., 2016 for further details). This evidence is intriguing for the theoretical and practical implications that it could have in the field of reading disorders, as already discussed in the previous section. Nonetheless, only behavioural measures have been employed to evaluate the performance of our participants and therefore, the conclusions drawn in Study 4 should only be considered as speculative. It would be valuable for future research to corroborate such behavioural evidence by employing neuroimaging techniques, such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and different methods including total brain volume, voxel- and surface- based morphometry, white matter, diffusion imaging, brain gyrification, and tissue metabolite to confirm hypoactivation of the VWFA (see e.g., Adrián-Ventura et al., 2020; Paulesu et al., 2001a; Ramus et al., 2018; Richlan, 2014). Future studies that use functional imaging to compare the performance of DD populations and typical developing readers in visual processing would prove valuable to test the assumption of a generalised visual impairment in DD.

Additionally, participants with DD both in the English and in the Italian sample showed great variability in terms of performances in all the tasks considered (Appendix A and B). In this light, large scale studies should be performed to understand whether DD operates as an umbrella term encompassing several different underlying problems, such as phonological and visual processing deficits (Giofrè, Toffalini, Provazza, Calcagni, et al., 2019). Unfortunately, the sample size of the studies presented in this thesis did not allow us to explore this hypothesis. Nonetheless, there is room to speculate that impairments in visual and phonological processing in DD are distributed around a continuum and therefore, individuals with DD may present with either a deficit in the visual or in the phonological domain or with a combination of both.

An insightful contribution to this claim was recently provided. A cluster analysis was conducted on a sample of over 300 Italian children with DD employing the Wechsler Intelligence Scale for Children – IV edition (WISC-IV, Orsini, Pezzuti, & Picone, 2012). The findings of this study indicated that the cognitive profiles of the DD children were grouped in two clusters: in one cluster, the children presented with marked deficit in phonological processing, however, more crucially, children belonging to both clusters manifested deficit in visual processing. The authors therefore concluded that the DD should be considered as a broad term, encompassing different subgroups (Giofrè, Toffalini, Provazza, Calcagnì, et al., 2019).

Following on from this point, although this aspect has been partly addressed by this thesis, large scale studies may strengthen the contention that different degrees of difficulties in phonological and visual domains may differentially impact on the manner in which reading is impaired in DD.

It would be also of interest to investigate visual and phonological processing in poor readers of other languages, such as German, Portuguese or French, whose orthographies are less consistent than Italian but more consistent than English to better understand any graduation of impact of visual processing in DD among orthographies with varying orthographic consistency.

Furthermore, it is worth noting that the studies within the thesis were conducted with highly educated adults with DD who are also likely to be highly motivated in their desire to read. Even though they still presented with poor visual and phonological processing, it is conceivable to hypothesise that they might have compensated for such phonological/visual impairments (Warmington, Stothard, & Snowling, 2013). Impaired phonological and visual processing might however have affected their reading performance in terms of accuracy and speed with deficit in visual processing affecting more speed, as seen in Study 1, Chapter 2 where participants with DD presented with a strong WLE.

It would be therefore of particular interest to investigate the performance of a population of young people on visual and phonological processing to understand how this double impairment would impact on the trajectory of reading accomplishment. A longitudinal study may help to establish this trajectory by assessing children at risk of developing DD on visual and phonological processing and see whether a combination of poor performance in visual and phonological processing may impact more on reading in terms of the manner in which reading is achieved. Large scale studies and longitudinal studies would also help disambiguate the issue whether visual deficit play a causal role in poor reading. Establishing a link between visual processing deficit and DD (e.g., measuring visual processing prior to the establishment of reading predicts later reading attainment see Rauschenberger et al., 2020), as well as demonstrating that training visual processing skills would lead to gains in reading ability would be key evidence to prove the causal impact of visual processing in DD.

It also worth noting that the studies presented in this thesis did not investigate the semantic corner of the triangle model. It is known that semantics plays an important role in reading, especially in the case of those words with exceptional spelling to sound mapping (i.e., irregular words). Given that opaque languages such as English may rely heavily on knowledge to access reading of exceptional words compared to transparent languages, then it would be possible that individuals with DD reading of opaque orthographies also present with semantic deficit. Further research would therefore be useful to disentangle this aspect.

Finally, the results presented in this thesis came from the investigation of DD in two alphabetic languages (i.e., English and Italian). However, there would be value in investigating whether and the extent to which the same dual deficit in visual and phonological processing consistently impacts reading in syllabic (e.g., Japanese Kana), morpho-syllabic (e.g., Japanese Kanji) and logographic (e.g., Chinese) orthographies (Siok, Perfetti, Jin, & Tan, 2004).

Studies investigating commonalities and differences in brain activation among these writing systems during reading would provide an interesting contribution to the topic (Wydell & Kondo, 2015). A meta-analysis carried out by Bolger et al. (2005), for instance, examined neuroimaging studies of word reading in English (alphabetic) readers, Chinese (logographic) readers, Japanese Kana (syllabic) readers and Japanese Kanji (morpho-syllabic) readers. The authors found that the same brain regions were engaged by readers of all the orthographic systems examined. However, some divergence in the localisation of brain activation within these regions suggested differences among the writing systems. Divergences were found in the left superior-posterior temporal gyrus (with more consistent activation for English and Kana but not for Chinese and Kanji), in the left inferior frontal gyrus and right occipito-temporal cortex (with more consistent activation for Chinese but not for English and Japanese).

The stronger activation for the alphabetic and syllabic writing systems in the left superior temporal gyrus was ascribed to the fact that the written symbols are mapped to more fine-grained speech sounds (phonemes and syllables), as opposed to whole-word phonology in Japanese Kanji and Chinese. Activation of the left inferior frontal gyrus in Chinese, would depend on the higher demand on integrated processing of semantic and phonological information in this writing system, which is required for unambiguous word recognition. Chinese includes a high number of homophones, therefore requiring additional support of the superior frontal gyrus (Richlan, 2020). Such evidence speaks for a common reading network across different writing systems, albeit with some differences accounted by the specificity of the writing system itself. (Bolger et al., 2005; Richlan, 2020)

With respect to DD, research investigating brain activation of individuals with DD in Chinese seems to indicate that at least in logographic orthographies, DD presents with greater hypoactivation in the middle frontal gyrus (Perfetti, Tan, & Siok, 2006; Siok et al., 2004). The argument raised by the authors of the study was that fluent Chinese reading relies on the integrity of the left middle frontal gyrus as a main hub for the coordination and integration of information in verbal and spatial working memory and that DD results from a failure of this brain region (Perfetti et al., 2006; see also Richlan, 2020 for a review). Despite the crucial role of the middle frontal gyrus in Chinese impaired readers, there is evidence that Chinese DD, similar to DD in alphabetic orthographies, showed hypoactivation in the temporo-parietal occipito-temporal and inferior frontal cortex. Such evidence suggests that a common underactivation of the same brain network, including temporo-parietal, occipito-temporal and inferior frontal cortex underlying deficit in DD across different writing systems with some orthography- related peculiarities (Richlan, 2020).

One may therefore speculate that poor readers in logographic writing systems (i.e., Chinese) present with less great hypoactivation of the VWFA compared to DD in alphabetic writing systems, especially the more transparent ones, such as Italian. As previously illustrated, VWFA tends to increase activation in response to unfamiliar stimuli and, with regards to reading, it results particularly activated in response to unfamiliar words, such as nonwords (Price & Devlin, 2011a) thus, being more engaged when smaller grain sizes are employed (i.e., sub-lexical reading) (Martin et al., 2016; Richlan, 2014; Schurz et al., 2010; Wimmer et al., 2010).

Chinese readers employ larger grain sizes to access reading, thus the reliance on the VWFA during reading might be reduced in this writing system. Similarly, even though Chinese DDs presented the same brain underactivation of DD readers of alphabetic orthographies including left occipito-temporal region and the VWFA, such underactivation might impact less on their poor reading performance.

Taking up with this point, the same kind of speculation might be put forward for syllabic and morpho-syllabic orthographies such as Japanese. Wydell and Kondo (2015), investigated brain activation of A.S., an English- Japanese bilingual, who was phonological dyslexic only in English, whereas his reading competence in Japanese was intact (see Chapter 1). According to the hypothesis of granularity and transparency (Wydell & Butterworth, 1999), phonological dyslexia is rare in those orthographic systems in which the speech-sound mappings are one-to-one (i.e., transparent) or in the case of opaque orthographic systems in which the orthographic units employed to represent sounds are coarse (e.g., whole word/character) (Ijuin & Wydell, 2018; Wydell & Butterworth, 1999a). The authors found that A.S. presented with a decreased activation in the superior temporal gyrus while reading in both English and Japanese. However, he struggled to read only in English whereas his reading performance in Japanese was comparable to his peers (Wydell & Kondo, 2015).

The left superior temporal gyrus is often implicated in sequential (sub-lexical) phonological processing, phonological short-term-memory and the temporary storage of phonological information (See Wydell & Kondo, 2015 for further details). The authors therefore concluded that the behavioural discrepancies presented by A.S. in reading fluency were caused by the difference in the two writing systems. English being an alphabetic system (employment of smaller grain sizes), requires more neural resources in the left superior temporal gyrus compared to Japanese which is a syllabic system (Wydell & Kondo, 2015). In the same way, one may speculate that, even though hypoactivation of the VWFA and therefore visual processing deficit, would play a role in the failure of fluent reading accomplishment in such a reading system (see Chapter 3), it might not be as determinant in Japanese as it is in alphabetic writing systems, especially those more transparent (i.e., Italian). Again, if confirmed with further research, these speculations would corroborate the argument of a biological unity in DD across orthographies, with some variations due to the specific characteristics of the writing system.

It is worth noting that lack of IQ matching and comorbidity exclusions may represent a limitation of the studies presented in this thesis. For instance, participants have not been matched for IQ. Given that participants have been recruited from different institutions, one may argue the IQ would be an issue and some variations on the IQ among the participants are possible. However, IQ is a very generic and broad concept, and indeed the use of some intelligence batteries has been recently questioned. For example, some authors (Giofrè & Cornoldi, 2015; Giofrè, Pastore, Cornoldi, & Toffalini, 2019) have highlighted important biases in the use of intelligence estimates in studies of children with learning disabilities. Principally, differences in IQs might reflect artefacts of the battery in use, rather than real differences in the proposed latent variables. This being said, the conclusions that can be drawn from the studies presented in this thesis might be strengthened if the results were replicated with appropriate IQ matching. Furthermore, it is worth acknowledging that perhaps in more differentiated samples the use of intelligence tests, may be worthwhile (see e.g., Kemp et al., 2009; Paizi, De Luca, Zoccolotti, & Burani, 2013).

Another potential issue is the comorbidity of the participants with DD with other SpLD (e.g., dysgraphia, dyscalculia etc.). Although individuals with DD along with other comorbidities may be more impaired than individuals that only present with DD (Toffalini, Giofrè, & Cornoldi, 2017), however, no differences have been found between DD and participants with other comorbidities in the tasks administered in both Italian (*p*s > .211) and English (*p*s > .103) (see Appendix D for details on the means, standard deviations and effect sizes). It is worth noting that English DD and the comorbidity group differed in the Checkerboards RTs ($F(1,16)= 5.24$, $p = .04$, $\eta_p^2 = .247$) with individuals with comorbidities performing worse than DDs and in the digit span task ($F(1,16)= 4.48$, $p = .04$, $\eta_p^2 = .230$) indicating that individuals with DD performed worse than the comorbidity group. However, given the small sample size (DD = 13, comorbidities = 5) such results seem to reflect more a type 1 error than real differences between the two groups.

To conclude, the aims of this thesis were: i) to investigate the crucial role of visual processing in DD among orthographies differing in the consistency of the writing systems, with the view to demonstrate that the phonological deficit hypothesis *per se* does not account entirely for poor reading in DD; ii) to demonstrate that DD is characterised by general visual-phonological impairments that are not restricted to reading but that influence reading acquisition and that such impairments are better accounted for by the primary systems hypothesis; iii) to provide evidence that, although the biological correlates of DD seem to be the same across different languages, the behavioural manifestation of DD may depend on the peculiarity of the orthographic system and this aspect is particularly true for visual processing deficit.

All these aims have been addressed in this thesis and the findings support the contention that DD is an umbrella term in which different cognitive mechanisms play a role in its manifestation. Phonological and visual processing, in particular, were the strongest predictors of fluent reading, thus confirming that impaired visual processing has a detrimental impact on reading achievement. Crucially, these findings speak in favour of general phonological and visual processing deficit in DD which are not restricted to reading as postulated by the primary systems view, which in turn cause general impairment in phonological and visual processing. Finally, visual processing was more impaired in DD readers of transparent orthography than in DD readers of an opaque orthographies. This evidence leaves room to speculate that behavioural manifestation of DD is linked to the specific characteristic of the orthographic system. The implications of this research are therefore important and relevant to the existing literature on DD but also for the clinical implications that it has in terms of assessment and remediation of DD.

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Appendix A Visual and phonological impairments in Italian DD readers

The aim of Study 2 presented in Chapter 3 was to evaluate whether both phonological and visual domains might be impaired in DD in a transparent orthography (i.e., Italian) as they seem to be in an opaque orthography (i.e., English, Study 2). The question is of crucial importance as English, with its high degree of inconsistency (i.e., the letter-sound correspondence is generally one-to many) is indeed considered as an "outlier" at least among the European orthographies (Share, 2008a). Consequently, generalising the findings from such an outlier orthography to the more widespread less opaque orthographies might be somewhat problematic.

The scope of this study was to investigate whether individuals with DD in a transparent orthography, such as Italian, struggle when processing visually complex stimuli as well as phonological material. More specifically, whether the same results obtained with English individuals with DD might be generalised to more consistent/transparent orthographies.

Introduction

Although it has been demonstrated that DD has neurobiological origins and biological unity (see Paulesu, 2001) a central role in reading disorders is determined by environmental factors, such as the consistency of the orthography in which the individual is learning to read (Landerl et al., 2013b; Richlan, 2020). A study conducted in thirteen different orthographies demonstrated that the orthographic depth plays an important role in literacy acquisition (Seymour et al., 2003). The depth of the orthography depends on the correspondence between the spoken and the written language, that is, the higher this correspondence the higher the consistency of the orthographies (Frost et al., 1987). Thus, inconsistent orthographies, such as English require much effort to the reader to accomplish fluent reading compared to more consistent orthographies, such as Italian. These problems experienced by unimpaired readers are even more evident in individuals with DD (Landerl et al., 1997; Moll et al., 2014).

Despite a body of empirical evidence of different manifestations of DD across orthographies, some authors argued that individuals with DD present with the same deficits that are independent from the orthography, and that lie within the phonological domain (Bruck, 1992; Ramus, 2001; Swan & Goswami, 1997; Vellutino, 2004; Ziegler & Goswami, 2005; Ziegler et al., 2003) (see Chapter 1 for a discussion on DD in different orthographies). This view of a unitary phonological deficit in DD has nonetheless been contrasted by evidence suggesting that impaired phonological skills might be one of the multiple cognitive deficits that interact to cause DD (see Elliot & Grigorenko, 2014). Some individuals with DD for instance, are characterised by a "*double deficit*" in phonological processing and in RAN (Bowers & Wolf, 1993; Norton & Wolf, 2012) (see Chapter 1 for details).

A cross-cultural study conducted to investigate the contribution of phonological skills (i.e., phonemic awareness and phonological short term/working memory) and RAN in DD clearly demonstrated that both phonology and RAN were strong concurrent predictors of DD and that their contribution to DD seemed to depend on the complexity of the orthography. More specifically, phonology and RAN were shown to be stronger predictors of DD in more complex orthographies. The authors therefore concluded that both RAN and phonology are crucial predictors of literacy acquisition among orthographies with different orthographic complexity; however their impact on causing DD seems to vary across orthographies (Landerl et al., 2013b).

Remarkably, other studies showed that RAN is the best predictor of reading fluency in DD particularly in transparent orthographies. In more regular languages, in which phonological demands decreases overtime, naming-speed deficits appear as a more stringent indicator for poor readers (Wolf & Bowers, 1999; Wolf et al., 1994) (see Chapter 1). Additionally, a study which explored visual processing in children differing in RAN speed, found that low RAN children also presented with a deficit in processing visual stimuli. (Stainthorp et al., 2010).

The evidence that RAN is a strong cross-linguistic predictor of DD and especially in transparent orthographies as well as its relationship with visual processing, strengthens the contention that impaired visual processing would be expected in transparent orthographies. In addition, according to the phonological deficit hypothesis, one may speculate that the results found in Study 2 of the impaired performance of English DDs in not only phonological, but also visual tasks may be replicated in this study with a population of DDs reading a transparent language (i.e., Italian). Such findings would be of crucial importance as they would confirm the double visual-phonological processing deficit in DD across orthographies varying in consistency. Moreover, as discussed in Study 2, such impairments in phonological and visual processing would be better accommodated by the primary systems hypothesis of which the triangle model is an instantiation (Patterson & Lambon Ralph, 1999; Woollams, 2014b).

To explore the aforementioned hypothesis of impaired visual and phonological processing in individuals with DD reading of a transparent orthography, a sample of Italian university students with childhood diagnosis of DD was assessed. The paradigm was the same employed in Study 2 with the English sample, thus encompassing visual, phonological and VSWM tasks. As for the VSWM, the rationale behind the investigation of the visuo-spatial component was the same as presented in Study 2. As already mentioned, there is clear evidence of impaired verbal WM in DD across orthographies whereas much less is known about impaired VSWM in poor readers. Interestingly, Study 2 demonstrated that English DDs performed worse than TDRs in VSWM tasks. Therefore, it would be of interest to investigate if the same impairment in VSWM may be found in DD in an Italian sample.

A number of predictions can be made in this study: 1) comparably to the English sample, the Italian participants with DD would perform worse than their matched controls in both phonological and visual tasks; 2) performance in VSWM tasks would also be impaired in the Italian sample as a consequence of a deficit in visual processing and especially in those tasks that require greater attentional control; 3) discriminant function analysis conducted to establish which predictors would better discriminate between DDs and TDRs would demonstrate that both phonological and visual processing are strong predictors of DD in Italian as well as in English, hence confirming the crucial role of both domains in DD across orthographies.

Notably, auditory processing was not evaluated in this study. The discriminant function analysis in Study 2 clearly demonstrated that phonological processing *per se* accounted for the variability of the two groups and therefore auditory processing appeared less relevant to discriminate between DDs and TDRs. Such findings are in line with previous literature, which showed that phonological processing deficit accounted for reading impairments in DD independently from an auditory deficit (see Ramus et al., 2003).

Method

Participants

Eighteen university students with DD (5 males; age range 19-26; M_{age} = 21.3; *SD* = 2.34) participated. All were native speakers of Italian and in receipt of a formal diagnosis of dyslexia (supplied by a registered assessor of SpLD), as required for access arrangements and additional support in Italian higher education institutions (see law 170/2010). Participants with DD have been contrasted to a typical developing readers (TDR) group comprising 18 students (6 males; age range 19-25; M_{age} = 21.17; *SD* = 1.85). The two groups did not differ statistically for gender, $\chi^2(1) = 0.131$, $p = .717$, Cramer's $V = .060$, or age, $F(1, 34) = 0.25$, $p = .876$, $\eta^2_p = .001$.

The reading level of the DD and TDR groups was assessed using two reading tasks (word and nonword reading see Cornoldi & Montesano, 2020). Since the error rates were not normally distributed in the two groups a Mann Whitney U test was performed. As expected, the TDR group outperformed the DD group in both word ($U = 312$, $n = 36$ $p < .001$) and nonword reading ($U = 242.5$, $n = 36$ $p = .01$).

Procedure

All tasks were administered using E-Prime 2.0 software (MacWhinney et al., 2001). Students with DD were assessed individually in a single session lasting approximately 1 hour in a quiet room at Università della Calabria (Italy). The TDR group was assessed at the University of Padova (Italy). The study was approved by the ethics committees of the University of Calabria and the University of Padova and written consent was obtained from all participants.

Materials

Visuo-spatial working memory tasks (Mammarella et al., 2018)

Three VSWM tasks were employed in this study: balloons, sequential matrices and simultaneous matrices. All of these tasks were of increasing difficulty. The procedure was the same adopted in the study with the English sample (see Chapter 3). To reiterate, in the balloons task, participants were presented with two sets of stimuli (i.e., balloons). Immediately after the first presentation each participant had to recognise the target balloons within a second set of stimuli comprising the same stimuli of the first set plus one or more distractors. In the sequential matrices task, participants were asked to recall the positions of black cells that appeared one by one for 1 second in different positions on a 5 × 5 grid. In the simultaneous matrices task, participants had to recall the position of a number of black dots, which appeared simultaneously for 3 seconds on a 5×5 grid. Participants were presented for 1.5s with a 5 × 5 grid (Giofrè & Mammarella, 2014; Unsworth & Engle, 2006; 2007).

Like in the English study, for balloons and simultaneous matrices, stimuli were simultaneously presented; therefore, the order of recalling was irrelevant for this task whereas for the sequential matrices task, participants had to recall the items in the right order of presentation. Therefore, only the stimuli recalled in the correct order of presentation were included into the score.

Visual matching tasks (Roberts et al., 2013)

Two visual matching tasks, checkerboards and Kanji, were employed to assess visual abilities (see Chapter 3 for details). For each of these tasks, RT and accuracy data were collected. A set of 32 black and white checkerboards and a set of 60 kanji characters were used. The stimuli differed for complexity and similarity, forming the visually simple and visually complex sets respectively.

Stimuli were used to form a triad-based matching-to-sample task, in which the probe was placed in the centre with the target and foil above or below. The position of the target was randomised across trials.

Three vertically aligned stimuli appeared on the screen for each trial and the participants had to decide whether the top or bottom stimulus matched the central one (i.e., they had to identify the target), by pressing two different keys on the keyboard ("N" for the stimulus below and "Y" for the stimulus above). Each participant was required to respond as quickly and accurately as possible.

Phonological tasks (WAIS-IV, Wechsler, 2008)

To investigate phonological processing the digit span test was used. As for the study with the English sample (Chapter 3), the span test score is obtained by summing up the scores in the three span conditions (see Wechsler, 2008 for more detailed information).

Results

Means and standard deviations for both RT and accuracy of the two groups are displayed in Table A.1.

Table 0.1. Mean scores and standard deviations (SD) obtained by the typical developing readers (TDR) and the Developmental Dyslexia. (DD) groups in all tasks. DD = developmental dyslexics; RT = reaction times

			Statistical analyses		
Task	DD	TDR	$F(1, 34)$	p	Cohen's d
VSWM					
Balloons	31.33(3.14)	33.11(2.32)	3.72	.06	.64
Sequential Matrices	35.17(10.57)	43.61(7.78)	17.76**	.000	.90
Simultaneous Matrices	41.61(4.68)	45.56(5.26)	5.65*	.023	.79
Visual					
Checkerboards RT	4535.51(2163.56)	1194.61(575.06)	24.48**	.000	2.11
Kanji RT	2802.38(1104.34)	1307.48(282.99)	30.95**	.000	1.85
Checkerboard ACC	0.97(0.03)	0.94(0.05)	5.08*	.031	.72
Kanji ACC	0.97(0.03)	0.95(0.02)	1.89	.177	.78
Phonological					
Span test	21.00(3.78)	31.00(5.81)	37.40**	.000	2.04

Note. TDR = typical developing readers; ACC = accuracy; .000 means that the value is zero when approximated to the third decimal. * $p < .05$, ** $p < .01$.

Data analyses

SPSS (IBM, 2017) was used to perform all analyses. Before conducting the discriminant function analysis, issues related to sample size and multivariate normality were addressed (Tabachnick & Fidell, 1996b). The criterion that the sample size of the smallest group should exceed the number of predictors was met. Group size was equal, ensuring multivariate normality.

VSWM tasks.

A MANOVA was performed comparing VSWM tasks (balloons, sequential matrices, simultaneous matrices) in the two groups (Figure 4.1). A significant group effect, $F(3, 32) = 5.76$, $p = .003$, $\eta^2_p = .351$, was found, with a large effect size. Participants with DD performed significantly worse than TDR in two of the three VSWM tasks, with effect sizes ranging from moderate to large. In the balloon task the difference approached significance ($p = .06$). The Follow up ANOVAs are presented in Table A.1.

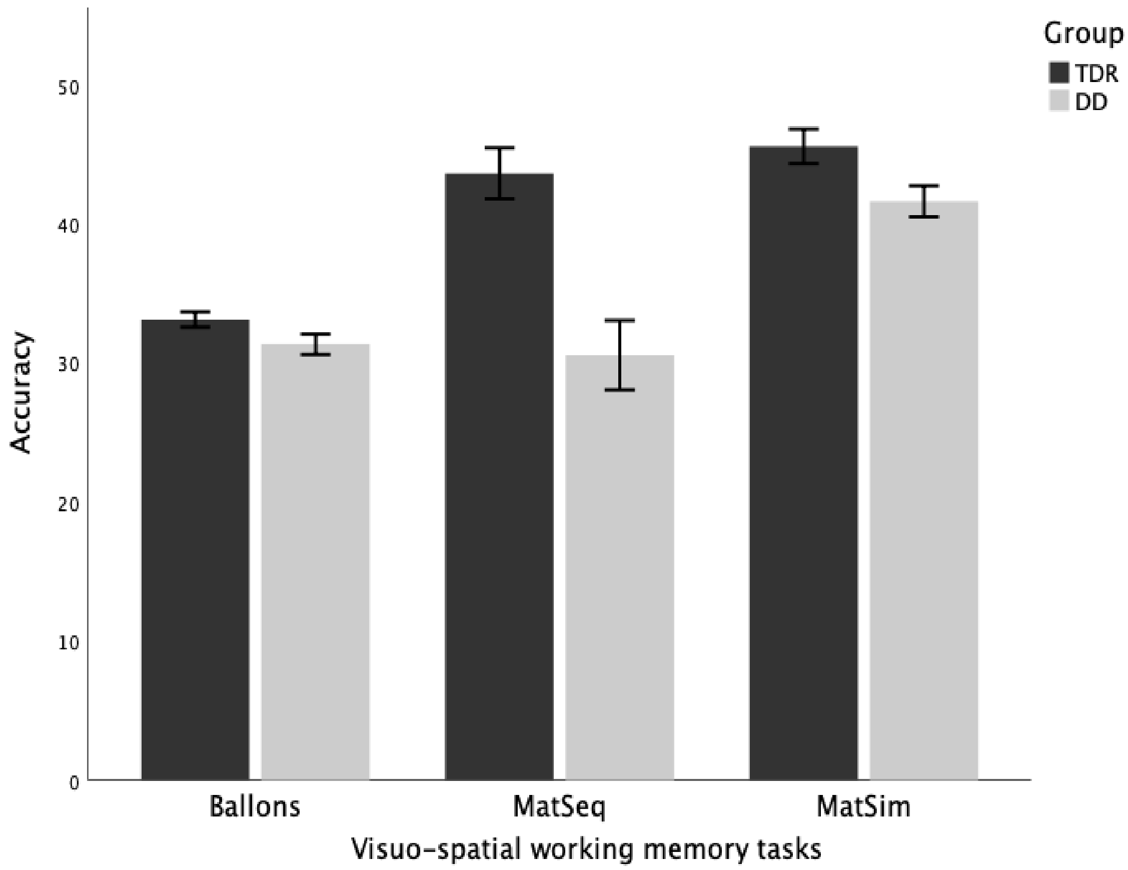

Figure 0.1. Accuracy on VSWM tasks. Error bars represent standard errors. TDR = typical developing readers, DD = developmental dyslexics.

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Visual processing

A MANOVA was performed comparing RTs in the visual tasks (Checkerboards and Kanji – Figure 4.2). A significant effect of Group, $F(2, 33) = 15.04$, $p < .001$, $\eta^2_p = .477$, with a large effect size was identified. Participants with DD performed worse than the TDR group in both tasks, with large effect sizes. A MANOVA was also performed for the accuracy of these tasks (Figure 4.3). The results showed no significant differences between the DD group and TDR group, $F(2, 33) = 2.57$, $p = .091$, $\eta^2_p = .135$. Follow-up ANOVAs are presented in Table 4.1 and demonstrate, for

Checkerboard task, the DD group performed significatively better than the TDR group. However, both groups reached a high accuracy rate, making very few errors.

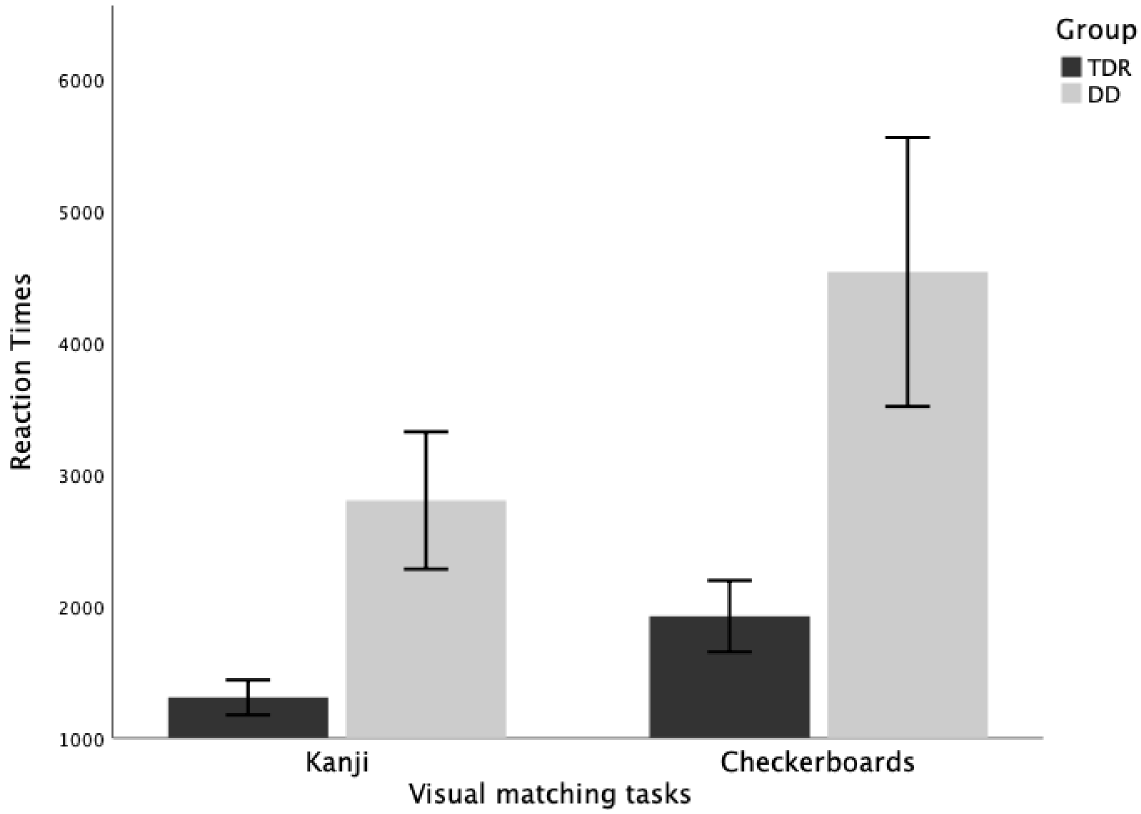


Figure 0.2. Reaction times on visual tasks. Error bars represent standard errors. TDR = typical developing readers, DD = developmental dyslexics.

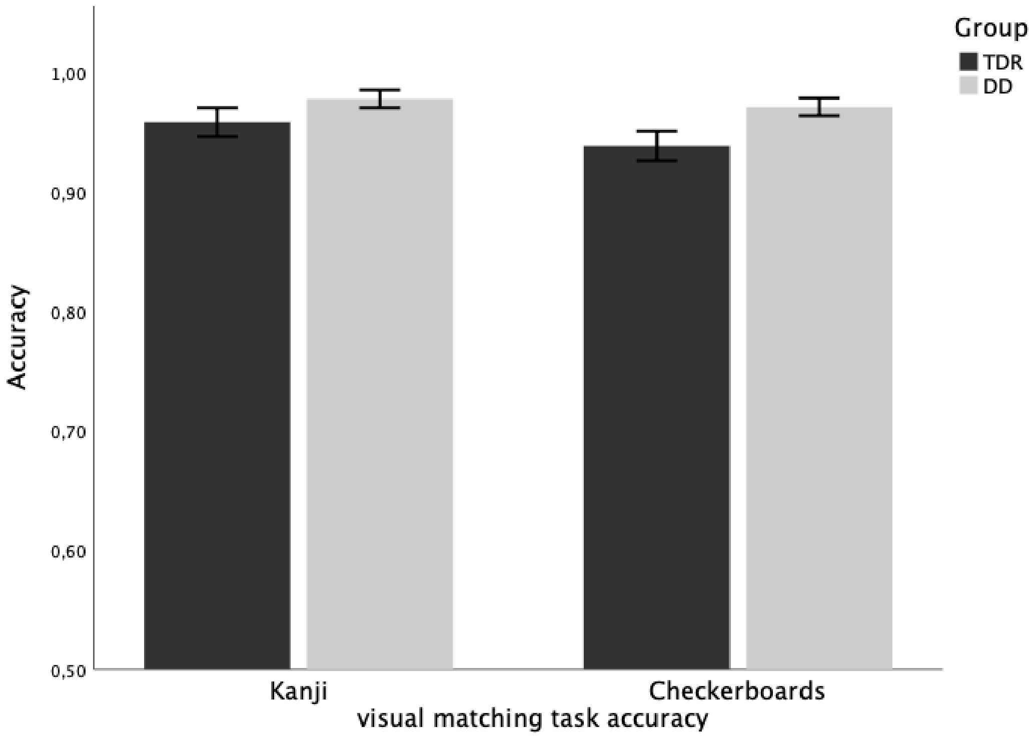


Figure 0.3. Accuracy on visual matching tasks. Error bars represent standard errors. TDR = typical developing readers, DD = developmental dyslexics.

Phonological processing

ANOVA was performed to compare the performances of the two groups (Figure 4.4). The results showed that the DD group performed worse than TDR group, $F(1, 34) = 37.40$, $p <.001$, $\eta^2_p = .524$, with a large effect size.

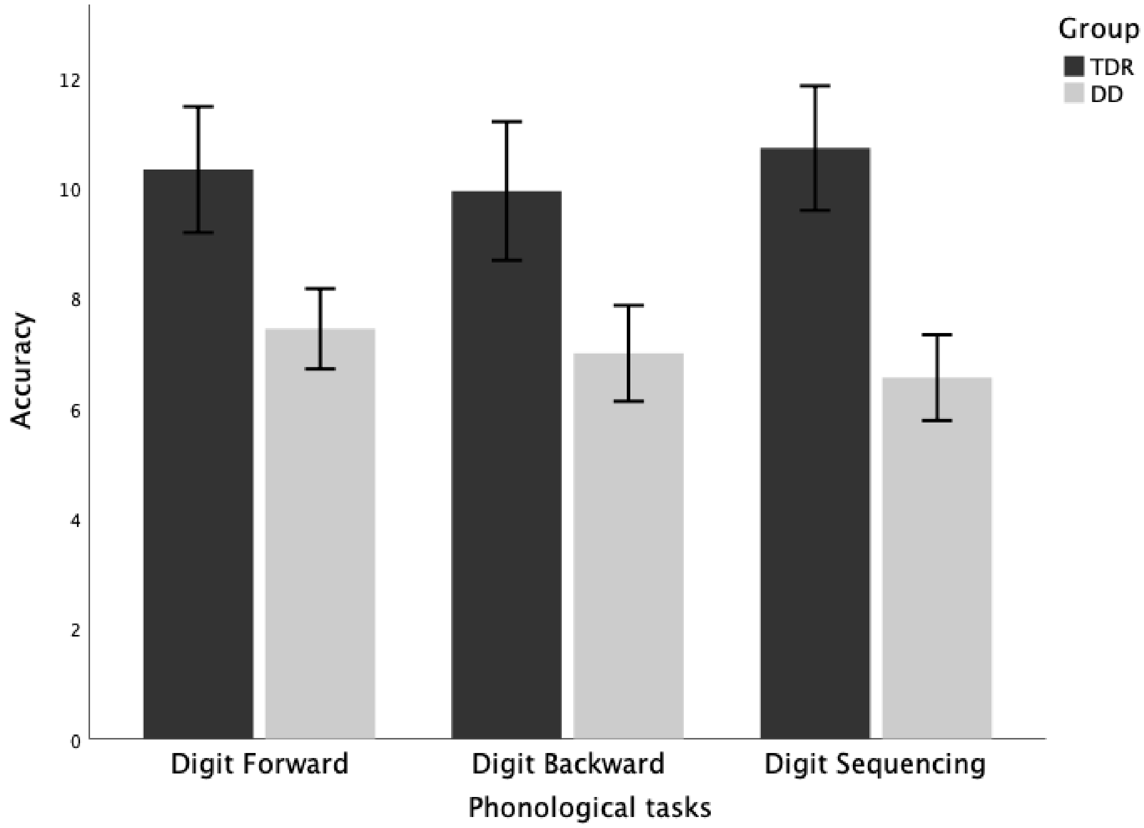


Figure 0.4. Accuracy on phonological tasks. Error bars represent standard errors. TDR = typical developing readers, DD = developmental dyslexics.

Discriminant function analysis

Similarly, to the English study (see paragraph 3.3.1 in Chapter 3 for further details), the discriminant analysis was conducted with the stepwise method, using all the tasks of the VSWM, visual and phonological tasks. Consistently with the results obtained with the English sample, a visual matching task (i.e., the Kanji task) and the phonological (i.e., the span test) task were included in the model. More intriguingly, in the Italian sample a VSWM task, the sequential matrices, also entered into the model to distinguish between TDR and DD group, with a Wilk's λ =.307.

The discriminant function analysis showed a reliable association with both the DD and the TDR group, $\chi^2(3) = 25.03$, $p < .001$. The Kanji task, the span test and the sequential matrix, were able to correctly discriminate 94.4% of the TDR group (i.e., 17/18) and 94.4% of the DD group (i.e., 17/18). Overall, the model was able to discriminate 94.4% of the participants. This finding indicates that these three tasks, i.e., Kanji, span test and sequential matrices had the greater discriminatory power as compared to all the other tasks included in this study.

Discussion

The aim of this study was to investigate the extent to which individuals with DD in a consistent orthography present with a wide range of impairments and especially in visual processing, as seen in Study 2 with English individuals with DD (Chapter 3). Analogously to the study with the English sample, the aim was to describe such impairments within the framework of the triangle model, an instantiation of the primary system hypothesis (see e.g., Woollams, 2014a). In order to achieve these aims a group of Italian participants with DD was compared to a matched group of TDRs using a comprehensive cognitive battery, including visual, visuo-spatial and phonological tasks.

Unsurprisingly, the DD group performed worse than the TDR on the span test, hence confirming the central role of phonology in DD which is independent of the orthographic consistency (Paulesu, 2001; Ziegler & Goswami, 2005; Ziegler et al., 2003). More critically, the DD group was impaired in processing non-orthographic visual stimuli, and in particular as indexed by RTs. These findings are similar to those obtained with acquired dyslexic patients (Roberts et al., 2013) and with English DDs and seem to confirm that a visual deficit is a common feature in DD irrespective of the orthographic consistency.

This study also aimed to investigate whether the visuo-spatial domain of WM is impaired in DD across orthographies. The results obtained in this study with the Italian DD sample confirmed those found with the English sample in Study 2 (Chapter 3), hence indicating that DD presents with deficit in VSWM and, more intriguingly, that such difficulties are independent from the orthographic consistency. It is worth noting that, as well as the English DDs, the Italian DDs were particularly impaired on those tasks that requires a higher placement of attentional control (Cornoldi & Vecchi, 2003; Kane et al., 2004). Interestingly, attentional control was hypothesised to positively impact reading proficiency (Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014). Therefore, poor performance of the DD groups in a VSWM task that requires greater attentional control (i.e., the sequential matrices) may indicate that they present with a deficit in this mechanism which in turn may cause poor reading.

This study also aimed to investigate whether visual and phonological processing tasks could discriminate between DD and TDR group membership, as they did in the English DD population. This aspect is of great interest as it would confirm the presence of a double phonological-visual deficit in DD regardless of the orthographic consistency. The discriminant function analysis showed that the digit span and the Kanji task were best able to discriminate between the two groups, hence confirming the role played by the visual and the phonological domains in DD, which appear to be similar across orthographies with different degrees of consistency. Given that both visual and phonological tasks were required for successful discrimination supports a position of both phonological and visual processing skills being impaired in the dyslexic profile irrespective of the orthography.

These results again support the argument that DD is characterised by a general impairment in processing visual and phonological information. Such an account is accommodated by the triangle model, a domain general model in which reading difficulties may be a consequence of damage to the phonological and visual systems, which in turn produces difficulties in reading along with impaired phonological or visual processing (see Woollams, 2014a).

Intriguingly, along with the visual and the phonological task a VSWM task was also entered into the model to distinguish between Italian DDs and TDRs. This represents an interesting difference in the study carried out with the English sample and might indicate that a deficit in visual processing might be more severe in this sample, thus exacerbating the impairment in processing in the visuo-spatial domain of the WM. The additional role played by a VSWM task in distinguishing among DD and TDRs in this study, but not in Study 2 with the English participants raises the possibility that, despite the universality of visual processing impairments in DD, the extent to which such impairment impacts reading may vary across orthographies with differing consistency. If this hypothesis is confirmed, then it may have several repercussions for the assessment and remediation of DD in different orthographies.

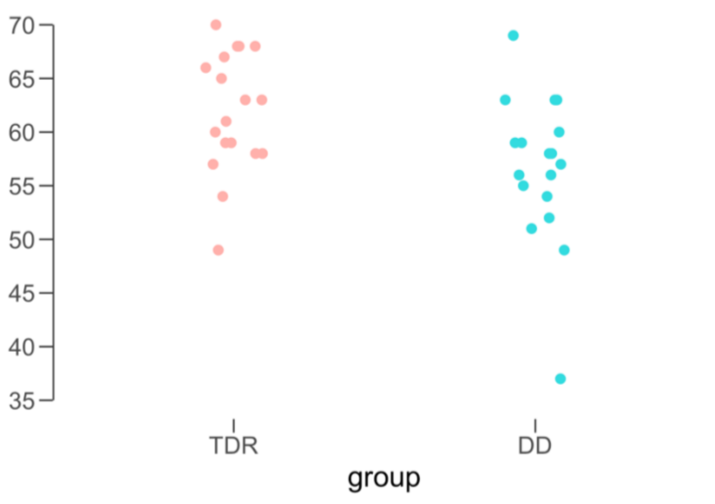
However promising for the impact they may have on our understanding of DD, the conclusions drawn here are merely speculative and further research is needed to confirm the different contributions of visual impairment in DD across orthographies. It would be worthwhile, for instance, to compare English and Italian DDs on visual processing tasks to evaluate whether the two groups perform differently in these tasks. This would be of a great relevance as this would indicate that, despite a biological unity in DD (see Paulesu et al., 2001a on this point), the behavioural manifestation of this reading disorder might depend on the characteristics of the orthography.

In conclusion, this study further confirms the role of phonology in impaired reading in DD. It also presents with several aspects of novelty compared to previous research and confirms visual processing deficit in DD. Given that the results of this study with Italian DDs mirrored the previous findings with the English DD group presented in Study 2, one may hypothesise that a deficit in processing visually demanding stimuli may impact fluent reading and that this impact is independent from the orthography, albeit it might be mediated by the transparency of the orthographic system.

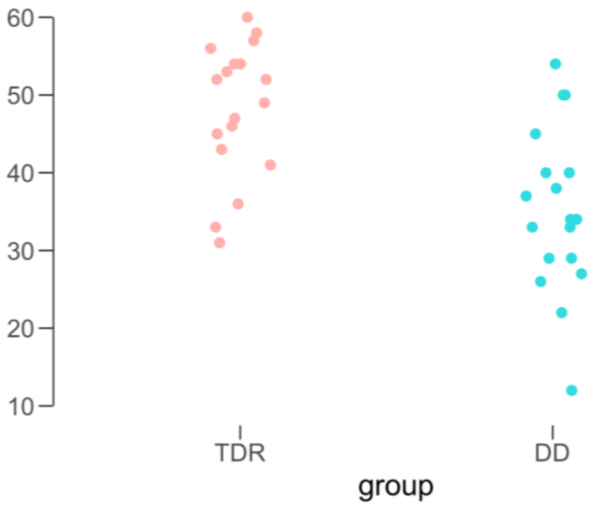
Appendix B English performance in the visual, visuo-spatial and phonological tasks

Balloons

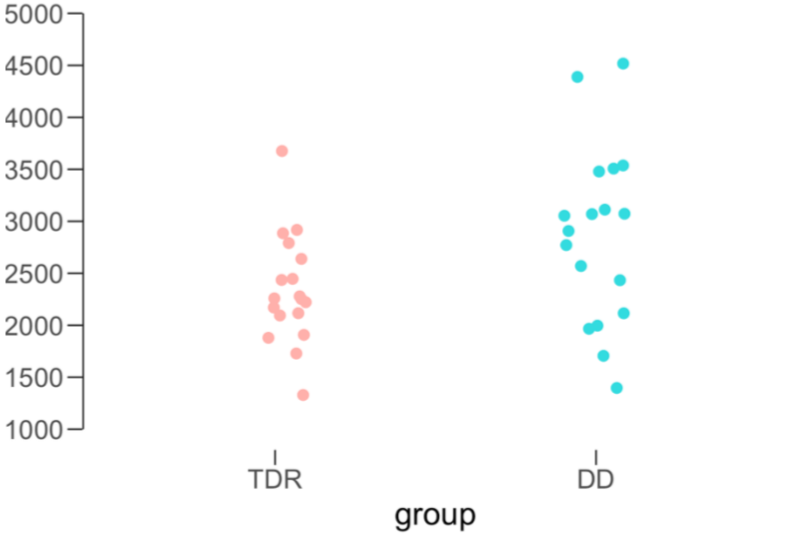
Simultaneous Matrices



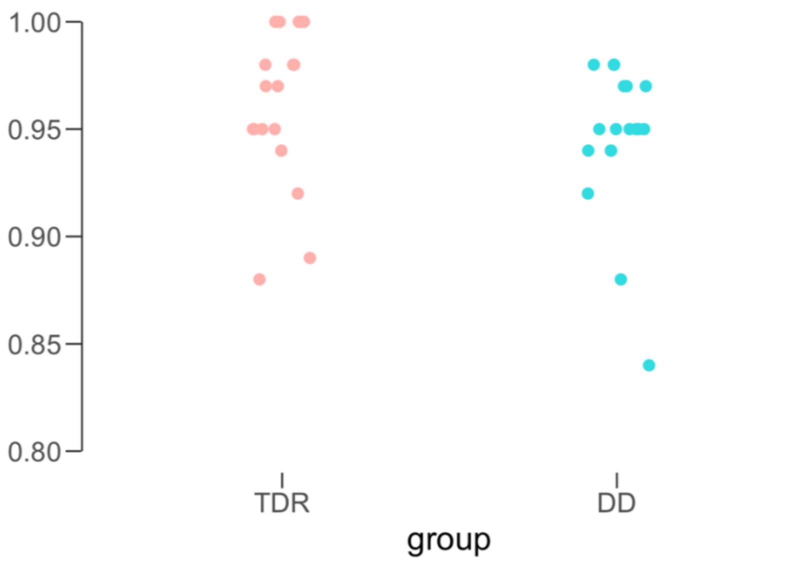
Sequential matrices



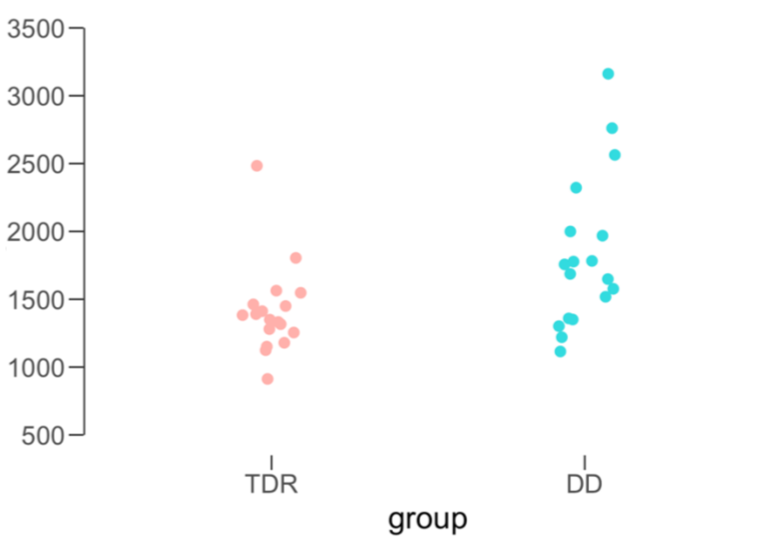
Checkerboards RT



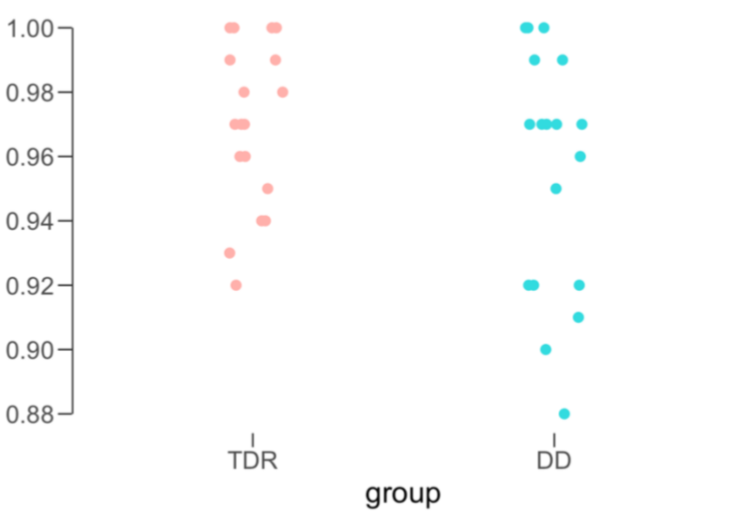
Checkerboards accuracy



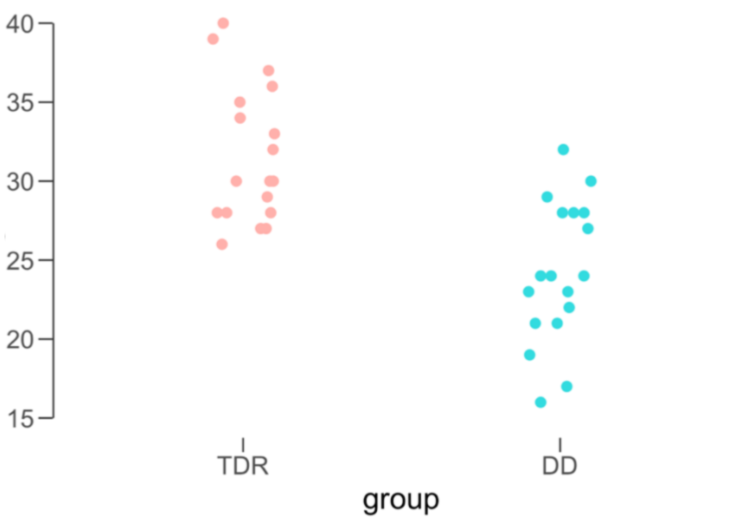
Kanji RT



Kanji accuracy

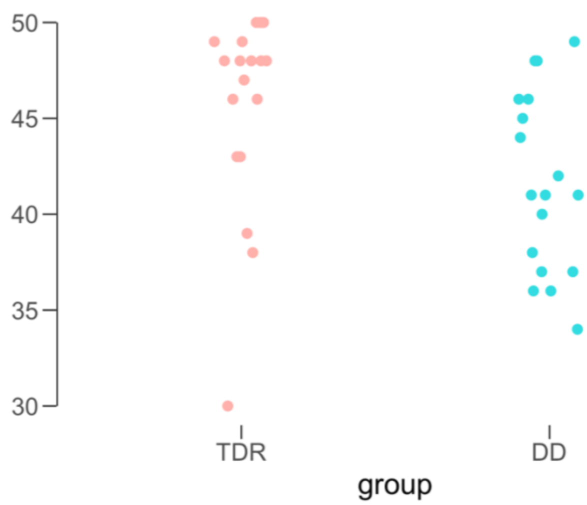


Digit span

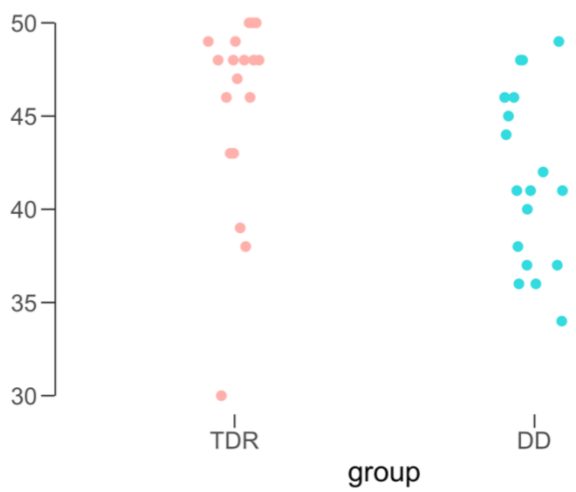


Appendix C Italian performance in the visual, visuo-spatial and phonological tasks

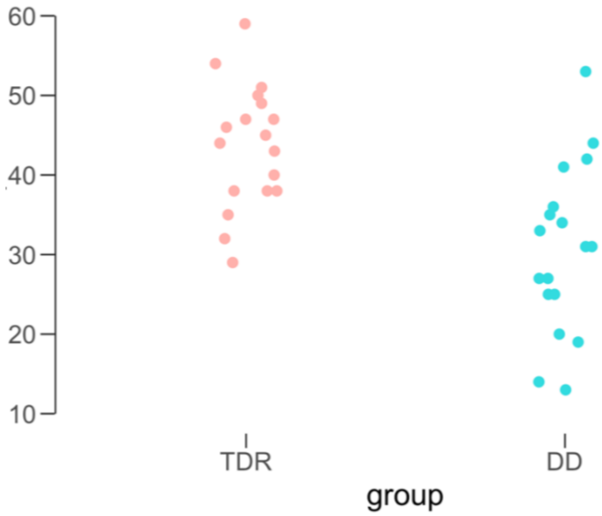
Balloons



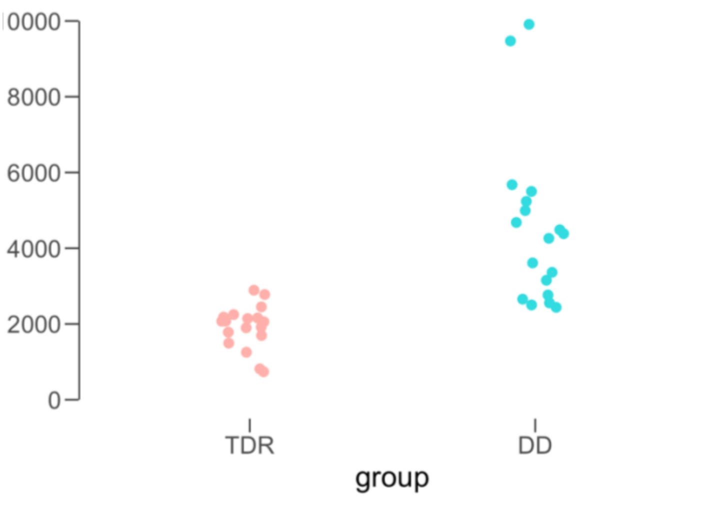
Simultaneous matrices



Sequential matrices

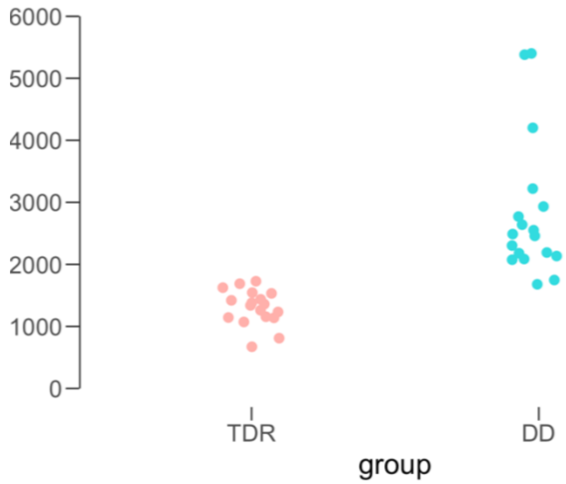


Checkerboards RT

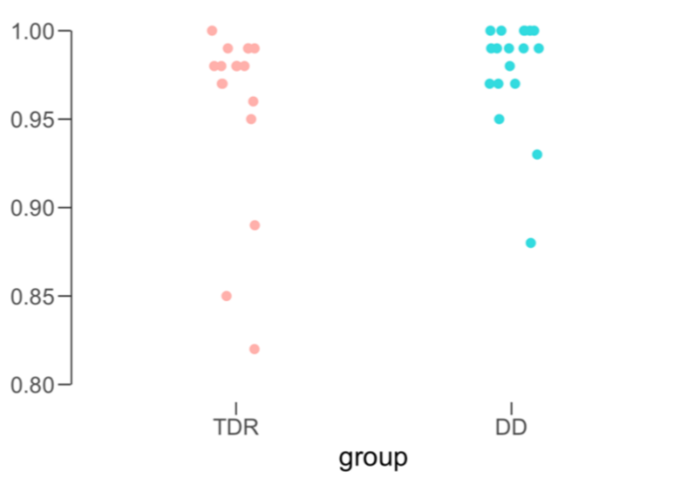


Checkerboards accuracy

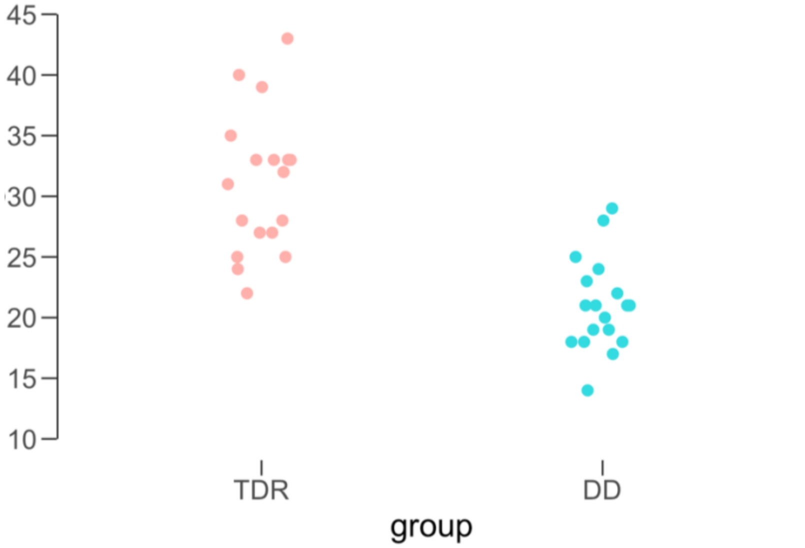
Kanji RT



Kanji accuracy



Digit span



Appendix D Comparison between DD and comorbidities groups in English and Italian

Table D.1. Mean scores and standard deviations and effect sizes obtained by the (DD) and the comorbidities groups in all tasks. DD = developmental dyslexics; RT = reaction times; η_p^2 (partial eta squared)

	Italian			English		
	DD (N = 7)	**Comorbidities (N = 11)**	η_p^2	**DD (N = 13)**	**Comorbidities (N = 5)**	η_p^2
Visual matching						
Checkerboard RT	4630.04 (2567.37)	4475.35(1998.16)	.001	2610.67(597.49)	3531.08(1122.51)	.247
Kanji RT	2932.38(1149.99)	2719.65(1122.68)	.093	1692.74(456.26)	2173.42(702.85)	.157
VSWM						
Balloons	31.00(3.46)	31.54(3.07)	.007	31.46(3.25)	28.40(6.50)	.102
Simultaneous Matrices	41.14(3.57)	41.90(5.41)	.007	55.07(7.51)	60.60(2.30)	.136
Sequential Matrices	29.14(9.38)	31.45(11.63)	.012	34.07(11.53)	38.00(7.84)	.029
Phonology						
Digit Span	19.57(1.61)	21.90(4.52)	.095	22.93(4.51)	27.60(2.20)	.230