INVESTIGATING ATTENTION IN DEVELOPMENTAL DYSLEXIA USING NOVEL MATCHING APPROACHES AND CHARACTERISING INDIVIDUAL READING PROFILE

Nicole Rebekah Stefanac

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School of Psychological Sciences and Turner Institute for Brain and Mental Health

Faculty of Medicine, Nursing and Health Sciences

Monash University

Clayton

ABSTRACT

Developmental Dyslexia (DD) is a neurodevelopmental disorder characterised by difficulties with accurate and fluent word reading and/or spelling. Although DD is typically diagnosed on the basis of poorer than expected reading ability, there is increasing awareness of considerable variability in the types of reading difficulties that children with DD experience. In addition, children with DD present with a wide array of deficits that extend beyond explicit reading abilities.

Attentional and visual deficits have been well documented in DD samples and it is commonly suggested that attentional deficits may contribute to reading difficulties. However, there is little agreement on the profile of these deficits, with conflicting findings reported in the literature. One way to understand this variability is to leverage the heterogeneity commonly seen in DD samples and examine whether attentional skills vary as a function of a child's individual reading profile (i.e., relative lexical and sublexical abilities). Words of varying types are known to differ in their attentional requirements and children with DD exhibit difficulties across these word types to differing degrees. It follows that variability in attentional deficits may be associated with the kinds of reading difficulties children with DD experience and that this could help explain the inconsistent results across studies. Despite this, individual reading profile has been infrequently considered in the research examining attention in DD.

Given learning to read leads to the refinement of neural networks involved in reading, including attentional networks, there is debate as to whether attentional deficits precede reading difficulties and interrupt typical reading acquisition or if they arise as a result of reduced reading experience and exposure to text. To move our understanding forward, research methodologies that can identify whether attentional deficits exist over and above reduced reading ability, or if they are present in all children with immature reading networks are needed.

The overarching objectives of this thesis were to explore the potential role of reading profile in explaining the variability in attention deficits observed in children with DD, and to clarify the direction of the association between these attentional deficits and reading development. These objectives were addressed in three empirical studies of children with a confirmed (and sole) diagnosis of DD who were compared with age matched controls as well as reading matched controls. Attention was examined using a range of standardised and experimental measures. The first study investigated reported behavioural symptoms of attention deficits using the Conners 3 parent-rated attention deficit hyperactivity disorder (ADHD) symptom questionnaire (Chapter 5), the second explored the cognitive mechanisms underlying visual attention span deficits through computational modelling on the Theory of Visual Attention (TVA) paradigm (Chapter 6), and the third examined performance on a perceptual decision making task assessing visual motion processing using electroencephalography (Chapter 7).

Results indicated that on the whole, children with a sole diagnosis of DD experienced significantly more attentional deficits than their same-age, typically developing peers. As a group, they were rated as having greater behavioural symptoms associated with ADHD, demonstrated considerably slower uptake of visual stimuli, and dysfunction in the way in which they accumulated evidence to make a perceptual decision about visual stimuli. Some of these deficits occurred over and above reading ability (e.g., behavioural inattention and executive functioning problems as well as evidence accumulation at the neural level) while others were comparable to reading matched controls (e.g., processing speed measured using the TVA). Notably, across all studies, reading profile moderated the association between reading ability and attention. Specifically, children with DD whose reading profile was characterised by relatively poorer lexical than sublexical skills presented with greater attentional and visual deficits.

The results from this thesis confirm that in addition to core reading difficulties, children with a sole diagnosis of DD experience attentional deficits that are likely to be impacting on functioning. However, not all attention deficits are unique to DD (after accounting for reading ability) pointing to a more nuanced relationship between attention and reading than previously thought. Furthermore, not all children with DD experience attentional and visual deficits. Instead, reading profile dissociated children with DD across the spectrum of attention abilities. The study findings speak strongly to the importance of assessing attention when working with children who have a diagnosis of DD. They also highlight the potential utility of using reading profile as a candidate for identifying which children with DD are more likely to experience co-occurring attentional deficits and to tailor treatment. From a theoretical perspective, the findings challenge the notion of a single-deficit view of DD and prompt further investigation into how attention is involved in the acquisition of reading skills across development in both typical and atypical readers. Thus, the thesis provides support for dimensional approaches to explain deviations from the typical trajectory of development at the symptom level, seeking to uncover shared vulnerabilities and risk factors for symptoms that may be common across a wide range of neurodevelopmental disorders.

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DECLARATION

In accordance with Monash University Doctorate Regulation 17, the following declarations are made: I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes three original papers prepared for submission or published in peer reviewed journals. The core theme of the thesis is understanding attention in Developmental Dyslexia as a function of reading ability and reading profile. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, the student, working within the School of Psychological Sciences and Turner Institute for Brain and Mental Health and under the supervision of Professor Mark Bellgrove and Dr Megan Spencer-Smith. The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research. In the case of chapters 5 and 6, my contribution to the work involved the following:

Thesis Chapter	Publication Title	Publication Status	Nature and % of Student Contribution	Co-author Name(s) – Nature and % of Contribution	Student co-author
5	Identifying Children with Developmental Dyslexia At-Risk of Co-occurring ADHD Symptoms.	Submitted *Journal of Neuropsychology*	80% - Concept, design, recruitment, data collection, data analysis, manuscript drafting.	Mark Bellgrove (5%) Anne Castles (5%) Megan Spencer-Smith (10%)	No
6	Visual Processing Speed as a Marker of Immaturity in Lexical but not Sublexical Dyslexia.	Published *Cortex*	72.5% - Concept, design, recruitment, data collection, data analysis, manuscript drafting.	Megan Spencer-Smith (5%) Anne Castles (5%) Signe Vangkilde (2.5%) Méadhbh Brosnan (5%) Mark Bellgrove (10%)	No

I have not renumbered sections of submitted or published papers in order to generate a consistent presentation within the thesis.

Student Signature: Nicole Stefanac **Date:** 4-May-20

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the student's and co-authors' contributions to this work. In instances where I am not the responsible author, I have consulted with the responsible author to agree on the respective contributions of the authors.

Main Supervisor Signature: **Date:** 4-May-20

PUBLICATIONS AND CONFERENCE PROCEEDINGS DURING CANDIDATURE

Manuscripts Related to Research Presented in this Thesis

Stefanac, N., Spencer-Smith, M., Brosnan, M., Vangkilde, S., Castles, A., & Bellgrove, M. Visual processing speed as a marker of reading delay for lexical but not sublexical dyslexia. *Cortex, 21*(120), 567-581, doi:10.1016/j.cortex.2019.08.004.

Stefanac, N., Castles, A., Bellgrove, M., & Spencer-Smith, M. Identifying children with Developmental Dyslexia at-risk of co-occurring ADHD symptoms. *Journal of Neuropsychology* (submitted).

Stefanac, N., Zhou, S., Spencer-Smith, M., Castles, A., O'Connell, R & Bellgrove, M. Inefficient evidence accumulation in children with Dyslexia underlies slow perceptual decision making. *Brain.* (prepared for submission).

Conference Presentations

Stefanac, N., Spencer-Smith, M., Brosnan, M., Castles, A., & Bellgrove, M. Visual processing speed as a marker of reading delay for lexical but not sublexical dyslexia. *Australasian Cognitive Neuroscience Society 2018 Conference,* Melbourne, Australia.

Stefanac, N., Spencer-Smith, M., & Bellgrove, M. Attention and Developmental Dyslexia: The case for individual differences. *College of Clinical Neuropsychologist's Postgraduate Research Symposium,* Melbourne, Australia.

Stefanac, N., Zhou, S., Spencer-Smith, M., O'Connell, R & Bellgrove, M. Dysfunctional evidence accumulation in Developmental Dyslexia: Support for the neural noise hypothesis. *Australian ADHD Professionals Association,* Brisbane, Australia.

Stefanac, N., Castles, A., Bellgrove, M., & Spencer-Smith, M. Identifying children with Developmental Dyslexia at-risk of co-occurring ADHD symptoms. *89th International Neuropsychological Society Meeting,* Rio De Janeiro, Brazil.

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THESIS OVERVIEW

In accordance with Monash University guidelines, this work has been presented in a 'thesis by publication' format. The empirical chapters have been written as manuscripts and prepared for submission for publication, or published, in scientific journals. As a result, there is some unavoidable repetition throughout the thesis, particularly with regards to introductory comments and methodologies.

Three manuscripts have been prepared corresponding with chapters 5, 6 and 7. For empirical chapters, references have been included at the end of the respective chapter to retain authenticity. References for remaining chapters have been collated into a full list at the end of the thesis to facilitate readability. Where possible, the formatting of figures, tables and subheadings have been amended to maintain consistency with the rest of the thesis. Please note, however, that some unavoidable content differences may remain due to the individual restrictions of the journals to which the manuscripts were submitted.

ABBREVIATIONS

In alphabetical order

- Age Matched (AM)
- Attention Deficit Hyperactivity Disorder (ADHD)
- Autism Spectrum Disorder (ASD)
- Castles and Coltheart Test 2 (CC2)
- Centro-Parietal Positive Decision Signal (CPP)
- Combined Theory of Visual Attention (CombiTVA)
- Confidence Interval (CI)
- Developmental Dyslexia (DD)
- Diagnostic and Statistical Manual of Mental Disorders (DSM)
- Dual Route Model (DRM)
- Electroencephalographic (EEG)
- Event-Related Potentials (ERPs)
- Frontal Eye Fields (FEF)
- Full-Scale IQ Score (FSIQ)
- Intellectual Quotient (IQ)
- Intelligence quotient (IQ)
- International Classification of Diseases (ICD)
- Intraparietal Sulcus (IPS)
- Multi-Trace Memory (MTM)
- Perceptual Reasoning Index (PRI)
- Processing Speed Index (PSI)
- Reading Matched (RM)
- Research Domain Criteria (RDoC)
- Specific Learning Disorder (SLD)
- Standard Deviation (SD)
- Steady State Visual Evoked Potentials (SSVEPs)
- Temporoparietal Junction (TPJ)
- Theory of Visual Attention (TVA)
- Ventral Frontal Cortex (VFC)
- Verbal Comprehension Index (VCI)
- Visual Attention Span (VAS)
- Visual Cortex (V)
- Visual Short-Term Memory (VSTM)
- Wechsler Individual Achievement Test – Second Edition, Australian and New Zealand Standardised Edition (WIAT-II-A&NZ)
- Wechsler Intelligence Scale for Children-Fourth Edition Short-Form (WISC-IV-SF)
- Working Memory Index (WMI)

KEY TERMS

Presented in the order they appear in-text

- Dyslexia
- Word-Blindness
- Congenital Word-Blindness
- Developmental Dyslexia
- Specific Learning Disorders
- Orthography
- Attention Deficit Hyperactivity Disorder
- Language Impairment
- Speech Sound Disorder
- Dysgraphia
- Dyscalculia
- Phonemes
- Graphemes
- Neuronal Recycling Hypothesis
- Phonological Competence
- Mental Lexicon
- Saccades
- Visual Word Form Area
- Dorsal Reading Route
- Ventral Reading Route
- Phonological Loop
- Articulatory Circuit
- Nonwords
- Sublexical Route
- Lexical Route
- Phonological Route
- Surface Route
- Semantic Route
- Direct Route
- Lexical Dyslexics
- Surface Dyslexics
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- Phonological Deficit Theory
- Rapid Automatised Naming Deficit Theory
- Perceptual Anchoring Theory
- Perceptual Anchors
- Magnocellular Deficit Theory
- Auditory Processing Deficit Theory
- Cerebellar Deficit Theory
- Statistical Learning Deficit Theory
- Dorsal Attention Network
- Ventral Attention Network
- Alerting Network
- Orienting Network
- Executive Network
- Hemispatial Attentional Neglect
- Attention Deficit Theories
- Visual Attention Span
- Visual Attention Span Deficit Theory
- Crowding
- Visuospatial Attention
- Sluggish Attentional Shift Theory
- Pseudoneglect
- Visuospatial Deficit Theory
- Attentional Blink
- P-type Dyslexia
- L-type Dyslexia
- M-type Dyslexia
- Multi-Trace Memory Model
- Global Process
- Analytic Process
- Late-Selection Theory
- Early-Selection Theory

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PROLOGUE

Formal education is one of the most important early experiences for a child and is thought to provide the critical foundations upon which all later learning occurs. Reading skills in particular are essential for education, enabling the reader to access knowledge about an array of topics and facilitating subsequent learning opportunities. Current educational policies emphasise the right of every child to attend an inclusive school, where social, emotional and educational needs are met in a supportive environment (The Victorian Department of Education and Training, 2017). However, at least 10-16% of Australian children struggle to acquire core academic skills such as reading, and do not receive necessary assistance (Louden, 2000). This places them at-risk of long-term poor self-esteem and social isolation (Bryan, Burstein, & Ergul, 2004; Humphrey, 2002; Svetaz, Ireland, & Blum, 2000), behavioural issues (Nelson & Harwood, 2011), poor school outcomes (Deshler, 2005; Scanlon & Mellard, 2001) and reduced occupational achievement (Waring, Prior, Sanson, & Smart, 1996). Addressing shortcomings in our understanding of developmental disorders in reading is therefore paramount to providing more accurate diagnoses and evidence-based assistance for individuals who are unable to flourish in the current educational system, and whose experiences are presently defined by an overwhelming sense of failure.

CHAPTER ONE: DEFINING DEVELOPMENTAL DYSLEXIA

The term *Dyslexia* was first used in 1887 by Rudolf Berlin, a German ophthalmologist, to describe a form of *word-blindness* found in adults who had suffered head trauma. Their symptoms were characterised by at least a partial disruption to their ability to decode written symbols and text, thought to be the result of brain lesions. Here the focus was on an acquired deficit, as opposed to that which develops naturally from a young age. The notion of a developmental analogue came later in 1896 when W. Pringle Morgan first described a child who failed to learn how to read and displayed similar symptoms to those characterised by Berlin. He therefore coined the term *congenital word-blindness* which was subsequently replaced with *Developmental Dyslexia* (DD). Despite extensive research since this time, questions regarding the existence and validity of DD remain at the forefront of educational policy and academic debate. These questions persist, at least partly, due to a lack of consensus on a definition for DD that is both precise and operationalised. In turn, this impedes clinical diagnosis and hampers remediation efforts.

This introductory chapter provides a background to DD, first presenting an overview of *Specific Learning Disorders* with a focus on recent changes in diagnosis and clinical classification. The process of learning to read in a typical context is then summarised, providing a framework for understanding the heterogeneity in the types of reading difficulties that individuals with DD experience. An overview of the leading theories put forward to explain DD is then presented. Issues of heterogeneity and comorbidity in DD are described throughout, providing the background for subsequent chapters in this thesis.

Diagnosis and Clinical Classification of Developmental Dyslexia

Unlike other disorders that are categorical in nature and have discrete aetiology (e.g., cystic fibrosis and Huntington's disease), the DD label does not denote an explicit category of clinical symptoms. Instead, it represents the extreme lower end of a distribution of reading ability (Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). Thus, the current diagnostic approach requires a somewhat arbitrary cut-off to be set on a continuous variable that describes reading abilities ranging from below age-expectations through to at, or above, average reading ability. Establishing agreement upon the reasonable statistical cut-off to determine whether an individual is impaired enough to warrant a diagnosis, and the appropriate components of reading to be measured, are therefore clear difficulties. An additional issue is that the DD term itself has been alternatively viewed as either different from, or synonymous with, other labels that describe literacy or learning difficulties. These include, but are certainly not limited to, reading difficulty, reading retardation, reading disability, specific reading impairments and reading differences. There are also numerous theories put forward to explain DD, giving rise to additional terminology used to describe the same clinical presentation of below age-appropriate reading.

Despite disagreement regarding performance cut-offs and terminology, it is widely accepted that the core problem of DD is an unexplained difficulty decoding text; that is, converting written, visual information into meaningful verbal output (Lyon, 1995). Previous versions of the Diagnostic and Statistical Manual of Mental Disorders (DSM: American Psychological Association, 2013) stipulated that to satisfy a diagnosis of DD, reading difficulties must be unexpected, with performance falling below the level predicted for both age and intellectual ability, as measured by an intelligence quotient (IQ). The logic underpinning this IQ-discrepancy approach was that difficulties should not be explained by impairments in intellectual functioning which were thought to place limits on the acquisition of academic skills such as reading. However, studies have repeatedly demonstrated that IQ is not a sufficient indicator of a fixed level of cognitive potential (Burden, Lidz, & Elliott, 2002; Sternberg & Grigorenko, 2000). Researchers have also described groups of significantly poor readers who have below-average IQ (often the result of associated limits in language skills contributing to a reduced overall average IQ score) that would therefore not satisfy the discrepancy requirements to justify their reading as 'bad enough' for a DD diagnosis (Fletcher, 2009; Stuebing, Barth, Molfese, Weiss, & Fletcher, 2008; Stuebing et al., 2002). As a result, the most recent DSM revision (DSM-5) implemented two major changes, each of which necessitated subsequent amendments: 1) adoption of an overarching category of learning difficulties referred to as Specific Learning Disorders with specifiers to characterise the nature of difficulty across three major academic domains, i.e., reading/spelling, writing and mathematics; and 2) elimination of the IQ-discrepancy requirement. Additional criteria requires that reading difficulties are present during school-age years, persist for at least six months and are pervasive in their impact on further academic or occupational achievement despite adequate formal instruction and attempts at remediation. Reading skills must also be substantially and quantifiably below expectations, although notably, this is considered at the discretion of clinical judgement.

Even though DD is characterised by problems that are circumscribed to a single skill, there is increasing awareness of significant heterogeneity in the difficulties experienced by those with DD (Murphy & Pollatsek, 1994; Pacheco et al., 2014; Zoubrinetzky, Bielle, & Valdois, 2014). Not only do individuals with DD exhibit significant differences in the types of reading difficulties they display, they also demonstrate variable deficits across a broad range of other cognitive skills including attention (Peterson & Pennington, 2015). Changes in the manifestation of these symptoms are also seen with age such that an individual with DD can present with a persistent but shifting array of difficulties across the lifespan (Adlof, Catts, &

Lee, 2010), making a consistent approach to both identification and remediation of DD challenging. Notably, reliable diagnosis can only occur at its earliest in the second or third grade of schooling (at approximately age 7 or 8), following repeated failure to attain age-appropriate reading skills. This is, paradoxically, typically after the crucial period in which intervention is expected to be most advantageous (Fletcher, 2009; Shaywitz, Gruen, & Shaywitz, 2007).

Prevalence of DD

In terms of epidemiology, DD is estimated to affect approximately 3-7% of the population worldwide (Lindgren, de Renzi, & Richman, 1985; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). It is widespread, with cases reported across all known languages and ethnicities (Landerl & Wimmer, 2000; Landerl, Wimmer, & Frith, 1997). Prevalence rates do, however, vary according to the definition adopted and the transparency of a language's written *orthography*, i.e., the degree to which a written language deviates from simple to one-to-one grapheme-phoneme correspondence (Brunswick, McDougall, & de Davies, 2010; Paulesu et al., 2001). There is a relatively small but significant male predominance (Quinn & Wagner, 2015; Rutter et al., 2004). However, the bias in favour of males in referred samples is even higher (Hawke, Olson, Willcut, Wadsworth, & DeFries, 2009; Jiménez et al., 2015; Miles, Haslum, & Wheeler, 1998), which is thought to reflect greater clinical attention as a result of increased rates of comorbid externalising behaviours (August & Garfinkel, 1990; Willcutt & Pennington, 2000).

Comorbidities in DD

DD is often diagnosed alongside other disorders, most prominently *attention deficit hyperactivity disorder* (ADHD), with 25-40% of children with one of these diagnoses meeting the criteria for the other (August & Garfinkel, 1990; Dykman & Ackerman, 1991; Gilger, Pennington, & DeFries, 1992; Willcutt & Pennington, 2000). ADHD is a complex condition beginning in childhood and characterised by age-inappropriate levels of behavioural inattention and/or hyperactivity/impulsivity (DSM-5, 2013). Worldwide prevalence rates estimate that 7% of children worldwide meet criteria for ADHD (Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). Despite their markedly different clinical profiles, DD and ADHD are comorbid at greater rates than is expected given their relative proportions in the general population (Boada, Willcutt, & Pennington, 2012). However, strict application of current diagnostic criteria for DD precludes a formal ADHD diagnosis as reading difficulties are required to be present in the absence of any other possible causes. As a result, nation-wide studies in the United States cite expected prevalence rates of reading disorders as actually being upwards of 20%, indicating that most children, at the time of diagnosis, are instead diagnosed as having ADHD given its more prominent behavioural phenotype (National Institute of Child Health and Development, 2006).

DD also frequently co-occurs with related developmental language disorders including *Language Impairment* as well as *Speech Sound Disorder* (Nittrouer & Pennington, 2010). Language Impairment is defined by problems in the development of structural aspects of language including syntax and semantics (Leonard, 2014a, 2014b). Speech Sound Disorder, on the other hand, is an inability to accurately and intelligibly produce the sounds required for successful speech (Shriberg, Tomblin, & McSweeny, 1999). Compared to DD, both Language Impairment and Speech Sound Disorder are often diagnosed prior to formal literacy instruction (Shriberg, Tomblin, & McSweeny, 1999) and therefore likely to be identified, and hopefully remediated, prior to presentation of DD.

Children with DD can also experience problems with a range of other academic skills (Berninger, Abbott, Thomson, & Raskind, 2001; Christopher et al., 2012; Landerl & Willburger, 2010). *Dysgraphia*, a disorder of written expression is often associated with DD (Nicolson, Fawcett, Brookes, & Needle, 2010; Nicolson & Fawcett, 1990) as is *Dyscalculia*, a specific deficit in the acquisition of arithmetic skills (Landerl, Fussenegger, Moll, & Willburger, 2009). As noted, the most recent revision of the diagnostic criteria acknowledges this high degree of comorbidity by grouping academic difficulties under the same Specific Learning Disorder umbrella. Thus, many children with DD have more than just one 'specific' disorder and are therefore expected to struggle more broadly at school.

In sum, children are diagnosed with DD on the basis of fundamental difficulties in reading, however, there is increasing awareness of significant variability in how this manifests. In addition, children with DD can present with a range of co-occurring deficits in other domains, reflected in high rates of co-morbidity with other developmental disorders, in particular ADHD.

Reading in Typical Circumstances

To explore reading related pathologies, one must first understand how reading occurs under typical circumstances. Successful reading involves interpreting verbal linguistic information (*phonemes*) from visual language stimuli (*graphemes*) representing speech codes and semantic concepts. In contrast to walking and talking, which are considered developmental milestones emerging with brain maturation, academic skills such as reading must be taught and explicitly learnt through environmental input and experience. Although often viewed as a predominantly a language-based task, reading requires the integration of a range of cognitive and perceptual skills such as visual attention, working memory and auditory sequencing to help support acquisition. Thus, reading skills are the result of opportunistic training of linguistic, as well as cognitive and perceptual neural networks, working together to support the conversion of text to sound (Dehaene & Cohen, 2007). In fact, research has shown that the brain contains a complicated but universal set of mechanisms that are attuned specifically to reading through experience (Bolger, Perfetti, & Schneider, 2005). Dehaene (2009) argues that to do this, human brain architecture obeys strong genetic constraints early in neuronal development, but then tolerates variability in response to the environment to accommodate reading. Coined the *Neuronal Recycling Hypothesis*, he posits that the brain re-allocates neural resources of less importance to facilitate connections needed to support reading. In fact, reading has been shown to occur at a cortical cost, with explicit instruction inducing competition between brain regions in the occipital lobe known to otherwise process faces and facial expressions (Dehaene & Cohen, 2011; Dehaene et al., 2010). Interestingly, cross-cultural analyses reveal that the cortical networks associated with reading exist consistently across all cultures, despite significant differences in the characteristics of written words across languages and their respective orthographies (Matthews et al., 2003). This suggests that despite major differences in the reading experiences across individuals, the human brain responds similarly to accommodate the conversion of written text to verbal speech under typical circumstances.

Learning to read.

Several developmental theories have been put forward to understand reading acquisition (Dickinson, McCabe, Anastasopoulos, Peisner-Feinberg, & Poe, 2003). Although there is some disagreement with respect to the order in which skills are proposed to develop, all theories agree that reading networks ‘piggyback’ core language abilities (Poe, Burchinal, & Roberts, 2004). Thus, reading actually begins with the early stages of language development, when the infant learns to differentiate auditory sounds. Knowledge of linguistic contrasts is thought to occur very early, with babies even a few days old being able to distinguish between simple sounds such as /ba/ and /ga/ (Eilers, Gavin, & Wilson, 1979). With increased exposure, a more diverse range of sounds and combinations are accumulated, and infants begin attempts at mimicking their production from approximately 6 months onwards (Eilers et al., 1979; Stuart & Coltheart, 1988). This auditory information is integrated within brain regions including the superior temporal gyrus and the inferior frontal gyrus (specifically the pars opercularis) and thought to be represented as various phonemic codes to be linked with visual material when reading instruction commences later on (Bailey & Snowling, 2002).

According to British psychologist Uta Frith (1985), children begin developing an understanding of the written word as distinct from other objects at around four years of age. From this point, they display common reading-like behaviours such as pointing to words and turning pages of books, usually mirroring the performance of their caregivers. Although words are still processed in the brain much like other visual stimuli at this age, activation of language-specific regions commences and undergoes continual refinement with increasing exposure to a range of texts, presented under varied conditions (Dehaene & Cohen, 2011). It is important to note here that other cognitive skills, such as control of visual attention, are developing simultaneously to accommodate reading such that children also begin to show differences in the way they attend to and take in text-based information compared with other visual stimuli (Plaza & Cohen, 2007).

Moving beyond the initial stages of reading and after the start of formal education, children begin learning how to decode words visually by breaking them up into their component graphemes and linking these to corresponding phonemes, e.g., breaking up the word “cat” into component sounds of /k/æ/t/ (Muter, Hulme, Snowling, & Stevenson, 2004). This grapheme-to-phoneme conversion requires the child to attend to smaller constituents of words, identify their sounds from phonemic memory stores and practice blending these together to assemble them coherently. These first years of training lead to the emergence of an explicit representation of visual codes and speech sound pairings, as well as the understanding that these are flexible enough to recombine to form new sounds and words, described as *phonological competence* (Muter, Hulme, Snowling, & Stevenson, 2004). Taught explicitly, phonological competence is thought to underpin initial reading acquisition (Seymour, Aro, & Erskine, 2003) and has been shown to distinguish between successful readers and those who are illiterate in these early stages of learning (Snider, 1997). With increasing ability and experience, representations then begin to emphasise syllables, syllabic distinctions and ultimately individual phonemes (Walley, Metsala, & Garlock, 2003). At the same time, the visual and attentional centres in the brain become better attuned to identifying and breaking down individual graphemes in text to support phonological competence (Dehaene & Cohen, 2011).

With continual gains in reading ability and exposure to text of increasing difficulty, decoding usually becomes less laboured. The child therefore attains a level of automaticity in their reading (Orsolini, Fanari, Tosi, Nigris, & Carrieri, 2006). Reading speed is no longer determined by word length or complexity, but rather by how often a word has been encountered (Share, 1995). New words with many links to other high frequency words tend to be read more quickly, reflecting increased involvement of prior experience and engagement of semantic networks (Landauer, Foltz, & Laham, 1998). At this stage, regular, high frequency words are often processed in parallel whereby entire grapheme sequences are taken in as wholes and compared to previously experienced words stored in a *mental lexicon* (Cunningham, Perry, Stanovich, & Share, 2002). Importantly, as these reading skills are advancing, neural networks both directly and indirectly related to language, including those that support reading, are further refined. This fosters ongoing gains in reading fluency and additional neural fine-tuning to allow for exposure to text of increasing complexity. Reading acquisition therefore represents an ongoing dynamic relationship between environment and biology that continues throughout development (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012).

Following rapid gains in kindergarten and the early years of primary school, typical reading trends indicate a significant deceleration in skill trajectory with age, demonstrating a plateau by late primary school/early secondary school (Logan et al., 2013). At this point, for most children, the focus of reading shifts to improving fluency and towards processing more complex components of text interpretation of sub-text implications as well as reading comprehension, allowing access to information about a wide-array of topics for ongoing learning (Billingsley, 2009).

The neuroanatomical basis of reading.

It is well-established that from a neuroanatomical perspective, the process of reading text begins with the written word processed via the visual system. Visual material is initially detected by the retinas in the eyes where specialised cells within the fovea are allocated to detect stimuli at fine enough resolution to allow for the recognition of print (Rayner, Murphy, Henderson, & Pollatsek, 1989). Given that only this small portion of the retina is useful for processing text, our gaze must travel in small steps across a page, known as *saccades,* to take in text-based information adequately (Vidyasagar & Pammer, 1999). The retina then transmits information to the occipital lobes via the lateral geniculate nucleus in the thalamus. It is important to note here that a number of higher-order visual attentional processes, as well as low-level sensory processes, influence the rate, type and amount of information that is attended to by the eyes, and therefore received by the brain (Lobier, Dubois, & Valdois, 2013; Sieroff & Posner, 1988).

Text information represented within the occipital lobes of the brain travels in a posterior to anterior fashion through regions referred to as V1-V5 (McCarley & Di Girolamo, 2001). This hierarchical stream corresponds to successive levels of processing, each step increasing in the complexity of analysis (Goodale, 2011; Mishkin & Ungerleider, 1982). At this point, all visual input is received bilaterally such that information presented to the left side of the visual field is transmitted to the right hemisphere and vice versa (Cohen & Dehaene, 2004). However, after initial processing, written text is quickly funnelled to the occipito-temporal region in the left hemisphere via the corpus callosum, indicating differentiation from other visual stimuli (e.g., faces and objects). This area, known as the *visual word form area*, is thought to selectively filter incoming visual information to detect the presence of text known to the viewer (Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). Discovered by Joseph-Jules Dejerine (1892) and confirmed by modern neuroimaging, the visual word form area has consistently been shown to activate in response to text in literate individuals from a range of cultures and therefore with exposure to various languages (Carreiras, Perea, & Grainger, 1997; Castro-Caldas et al., 1999). This area is also associated with the presence of letters and letter strings regardless of superficial changes in shape, size or position (Glezer & Riesenhuber, 2013). Once detected, the visual word form area forwards information to other cortical regions for conversion into sound and semantic interpretation via two distinct neuroanatomical circuits; the *dorsal* and *ventral reading routes* respectively (Jobard, Crivello, & Tzourio-Mazoyer, 2003). See Figure 1 for an illustration of the major brain regions associated with reading.

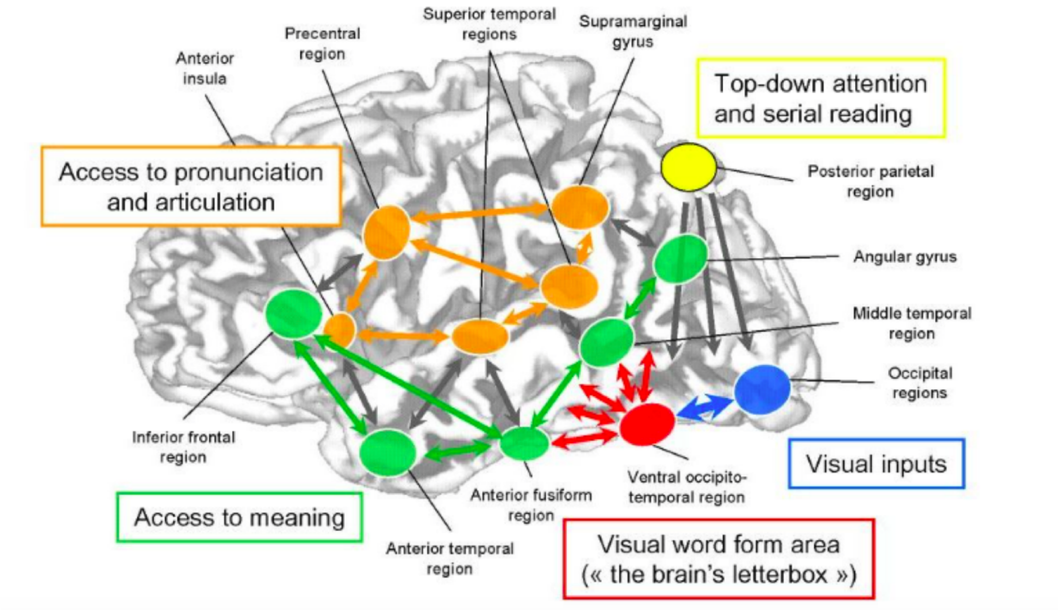

Figure 1. The major brain regions in the left hemisphere associated with reading as depicted by Stanislas Dehaene (2009). Top-down attentional processes (shown in yellow) initially influence the rate, type and amount of visual information received by the occipital lobes via the eyes and thalamus. The left occipito-temporal visual word form area (shown here in red) identifies the visual forms of letter and grapheme strings as distinct from other visual material. It then distributes this invariant visual information to dorsal and ventral brain regions to decode meaning and access articulatory codes for successful pronunciation (shown in orange and green respectively). Double-headed arrows linking orange and green nodes reflect bidirectional communication between both dorsal and ventral routes. Image taken from 'Reading in the Brain' by Stanislas Dehaene (2009, pp. 62).

The dorsal pathway.

The precise nature of the dorsal text-to-sound pathway is still relatively unknown. However, according to neuroimaging studies, converting text to speech initiates the activation of brain regions that are associated with verbal and auditory language analysis and production

(Broca, 1861; Lazar & Mohr, 2011; van Atteveldt, Formisano, Goebel, & Blomert, 2004). This involves the superior and middle temporal regions of the brain's left hemisphere, including Wernicke's area, the temporo-parietal junction and the planum temporale, as well as frontal zones such as the inferior frontal gyrus (including a portion of Broca's area known as the pars opercularis) and the supramarginal gyrus (Booth et al., 2002; Hickok & Poeppel, 2004; Jobard, Crivello, & Tzourio-Mazoyer, 2003; Saur et al., 2008; Taylor, Gozli, & Pratt, 2014). Electroencephalographic studies tracking the time course of the dorsal network indicate that the conversion of a word or grapheme into sound starts approximately 225 milliseconds after the letter first appears on the retina, with compatibility to a spoken sound recognised around 400 milliseconds (Raij, Uutela, & Hari, 2000). According to our current understanding, parsing graphemes into phonemes is most likely to be serial in nature, involving the segmentation of letters and words into their constituent parts and employing the planum temporale together with the inferior frontal gyrus to create a phonological circuit (Paulesu, Frith, & Frackowiak, 1993). It is thought that this *phonological loop*, often referred to in models of working memory as an *articulatory circuit* (Bayliss, Jarrold, Baddeley, & Leigh, 2005), is essential for storing phoneme segments, facilitating the blending of these together to form coherent words.

The ventral pathway.

Generally, inferior temporal regions are thought to contribute to the coupling of visual text with semantic knowledge via the ventral pathway (Carlson et al., 2014; Glezer & Riesenhuber, 2013; McCandliss & Noble, 2003; Pugh et al., 1999; Vinckier et al., 2007; Yeatman et al., 2011). However, these regions are not exclusively activated by the written word (Binder et al., 2006). Instead, posterior parietal regions including middle, angular and basal temporal gyri, as well as an alternative portion of the inferior frontal gyrus known as the pars triangularis (Jobard et al., 2003), are constantly active and continually access semantic information in the presence of both physical stimuli and internal thoughts about a wide array of meaningful concepts (Kotz, Cappa, von Cramon, & Friederici, 2002). In contrast to the visual word form area which is specialised in identifying when words are visually alike, e.g., “couch” and “touch”, regions within the left middle temporal cortex display sensitivities to words that are semantically related, e.g., “couch” and “sofa” (Mazoyer et al., 2007). Typically, these regions do not increase in activation at the presence of a written word, but rather, deactivate to a point below initial baseline levels whenever meaningless *nonwords* mimicking real words at the visual level are presented (Cohen & Dehaene, 2004). A known word is therefore thought to resonate in the temporal lobe, producing a wave of synchronised oscillations rolling through the cortex to contribute to meaningful encoding (Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Mazoyer et al., 2007). A meaningless nonword such as “trop” on the other hand, cannot induce a large enough wave of cortical activation for semantic recognition and phonological retrieval. In this case, reading instead relies on the dorsal network to successfully break down the word and access corresponding phonological information (Dehaene, 2009).

Although often described separately, the dorsal and ventral routes co-exist (Simos et al., 2002). They are linked via sub-cortical u-shaped feed-forward white matter tracts within the occipito-temporal cortex that innervate prefrontal and frontal brain regions (Catani, Jones, Donato, & Ffytche, 2003). This anatomy allows for a coordinated approach whereby ventral and dorsal routes work together to support seamless word reading (Zhou et al., 2016).

A cognitive model of reading: The Dual Route approach.

Although many cognitive models have been put forward to understand the process of reading (Rayner & Reichle, 2010), the most prominent is the *Dual Route Model* (DRM; Coltheart, Curtis, Atkins, & Haller, 1993). The DRM argues that following initial extraction of letter identity and location, reading text requires the contribution of two major processing pathways; the *sublexical* and *lexical* routes.

The sublexical route (also referred to as the *phonological* or *surface route*) supports the deciphering of words by breaking them down into their smallest graphemes and serially sounding them out to blend them into a cohesive word. This method is successful when confronted with regular words following strict phonological conventions, or words that are unfamiliar to the reader and therefore not already stored in memory, such as nonwords, e.g., “zop”. Recent studies demonstrate that the sublexical route converts consonants and vowels separately (Khentov-Kraus & Friedmann, 2018) and converts graphemes with sensitivity to phonological features (Friedmann, Gvion, & Nisim, 2015).

The lexical route (also referred to as the *semantic* or *direct route*), on the other hand, facilitates parallel processing of words as wholes by comparing these within a mental lexicon to retrieve corresponding verbal output based on previously learned information. When words are frequent but do not follow phonological conventions (i.e., irregular words such as “yacht”), they would therefore not be successfully read via the sublexical route. In these cases, reading usually requires a lexical, whole-word approach to recover its identity from memory for pronunciation (Seidenberg, 2005). See Figure 2 for a depiction of the steps underpinning the lexical and sublexical routes of the DRM.

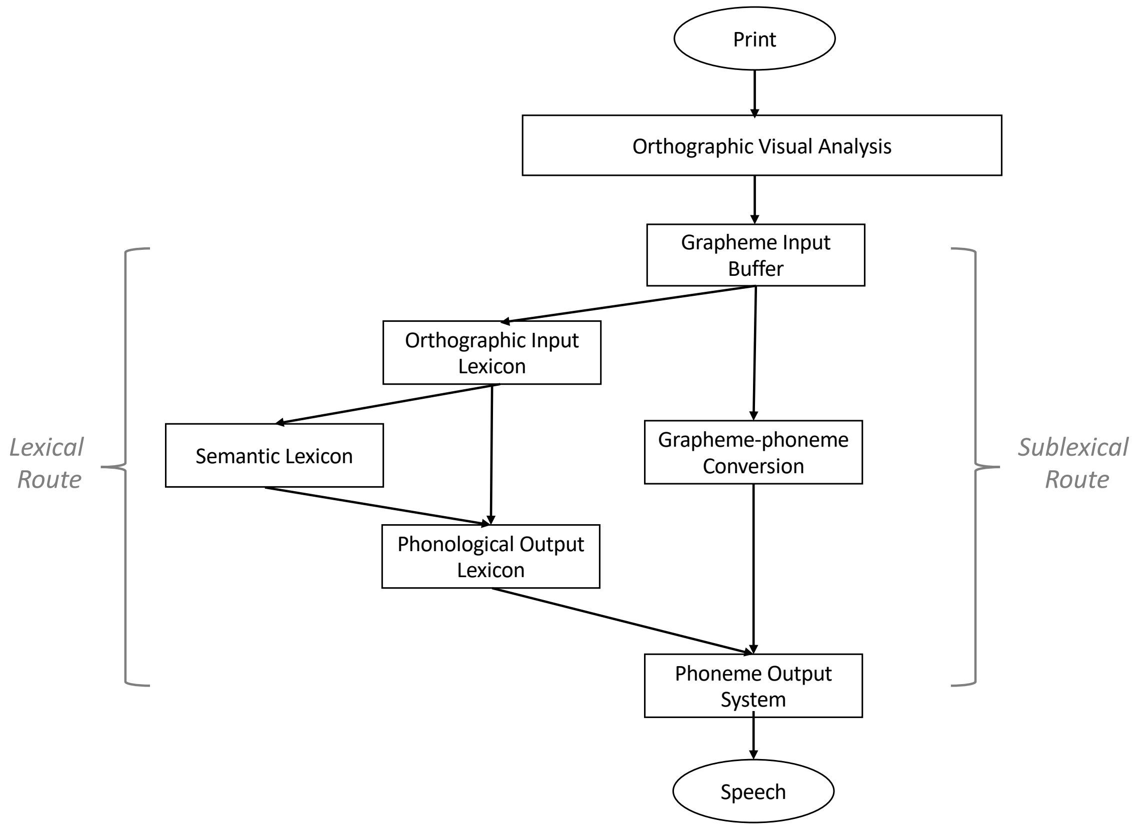

Figure 2. The Dual Route Model of reading adapted from the depiction by Max Coltheart in Snowling and Hulme's book "The Science of Reading: A Handbook" (2005, pp. 6-23).

Although the DRM of reading is often conceptualised as comprising these two distinct routes, much like the coordination of both ventral and dorsal anatomical networks, successful reading requires the joint activation of both sublexical and lexical processing routes. Although the nature of their integration is often debated (for an overview of both cascaded and connectionist approaches to the DRM see; Coltheart, 2006; Pritchard, Coltheart, Palethorpe, & Castles, 2012), it is widely agreed that lexical and sublexical routes converge with their relative contributions varying as a function of word characteristics such as familiarity, length and regularity (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Paap & Noel, 1991; Seidenberg, Waters, Sanders, & Langer, 1984). Importantly, the sublexical and lexical routes map neatly onto dorsal and ventral anatomical networks. Thus, the DRM is supported by longstanding neuroanatomical evidence of a dissociation between two key processing streams that come together to support reading (Hickok & Poeppel, 2004).

Heterogeneity of Reading Difficulties in DD in the Context of the Dual Route Model

Researchers have come to acknowledge the significant heterogeneity in the types of reading difficulties individuals with DD experience across various word types, i.e., regular versus irregular words (Peterson, Pennington, & Olson, 2013). Conceptualisation within the DRM of reading posits that reading difficulties can stem from deficits at any stage of processing along either the sublexical route, the lexical route or both. Extending the earlier work of Boder (1970), a reading impairment in the sublexical route of the DRM is thought to result in difficulty reading aloud unfamiliar words or nonwords but intact reading of words already stored in the mental lexicon. On the other hand, deficits along the lexical route are characterised by difficulty reading irregular words and words for which the grapheme to phoneme conversion is ambiguous with intact reading of regular words. The degree to which individuals with DD display problems in the lexical and sublexical pathways of reading has been shown to vary considerably (Ziegler et al., 2008). At one end of the continuum, there are some individuals whose reading profile is characterised by relatively poorer lexical reading, so-called *lexical* or *surface dyslexics*. At the other end, are those with relatively worse phonological skills, so-called *sublexical* or *phonological dyslexics* (Castles, Bates, Coltheart, Luciano, & Martin, 2006). Between these extremes, fall the majority of individuals who have less marked dissociation of lexical and sublexical skills, known as *mixed dyslexics*. Although some researchers have attempted to define these reading profiles statistically (Castles & Coltheart, 1993; Zoubrinetzky, Bielle, & Valdois, 2014), determining optimal cut-off criteria has proven problematic (McArthur et al., 2013; Sprenger-Charolles, Siegel, Jiménez, & Ziegler, 2011). In addition, sub-grouping fails to capture the variation across the entire spectrum of relative lexical and sublexical skills (Castles, Datta, Gayan, & Olson, 1999; Griffiths & Snowling, 2002), particularly for those with the most common reading impairments; *mixed DD*.

Current Causal Theories of DD

Despite the ease with which most people are able to integrate the abilities necessary for reading, converting text to sound relies on the careful co-ordination of a wide array of skills working in synchrony. Consequently, problems with a range of cognitive skills can impact on typical reading development and result in reading difficulties. Thus, researchers have long strived to find a single unique deficit responsible for DD. However, given significant heterogeneity in symptoms, a consensus remains elusive.

Initial investigations looked to the stages of the reading process that are disrupted in DD. Given phonological skills are commonly considered a foundation for reading acquisition, a phonological deficit has been suggested as being at the crux of DD (Stanovich & Siegel, 1994). According to this, impairments in linking visual material with corresponding auditory codes based on phonemic rules is impaired in DD. Although this *Phonological Deficit Theory* is prominent in the literature, it offers little understanding as to what initially causes this disruption to phonological acquisition. Furthermore, core phonological deficits do not explain all cases of DD, with a substantial number of individuals with DD demonstrating difficulty without notable problems with grapheme to sound conversion, i.e., lexical dyslexics (Heim et al., 2008; Zoubrinetzky, Bielle, & Valdois, 2014). Although these individuals may be captured by more comprehensive models of reading such as the DRM, these accounts still provide limited guidance as to the precise mechanism(s) that cause disruption to the normal acquisition of sublexical and/or lexical skills resulting in DD.

In addition to core reading difficulties, individuals with DD present with a wide range of sensory and cognitive deficits. Consequently, several alternative causal theories of DD have emerged. These propose that impairments in various sensory and cognitive abilities contribute to reading difficulties by impacting on either the acquisition of phonological information, or access to it. For instance, researchers have widely documented processing speed deficits in DD samples that culminate in difficulty quickly accessing and producing phonological labels for nameable stimuli such as digits, colours or objects, referred to as the *Rapid Automatised Naming Deficit Theory* of DD. According to this theory, reading difficulties arise as children with DD are unable to rapidly access and reproduce phonological outputs at a rate required to read fluently, despite their intact representations (Di Filippo et al., 2005; Georgiou, Parrila, & Kirby, 2009). However, arguments against this theory contend that even under untimed conditions, individuals with DD can present with poor phonological competence suggesting the problem is not only with speedy retrieval of phonological information but with their cognitive representation (Norton & Wolf, 2012; Wolf & Bowers, 2000). As a result, alternative sensory and cognitive theories speculate as to how the acquisition of phonological material is disrupted in DD. For instance, the *Perceptual Anchoring Theory* argues that individuals with DD have deficits in their ability to create and maintain connections between schemas of knowledge representing the identity of an object and its sensory attributes (i.e., forming *perceptual anchors*; Ahissar, Lubin, Putter-Katz, & Banai, 2006) but this has been difficult to confirm in all cases of reading impairment. There are also theories regarding low-level visual deficits such as impairments in the development of magnocellular neurons which affect coherent motion processing in DD (Stein & Walsh, 1997). Coined the *Magnocellular Deficit Theory* of DD, it is thought that these impairments in processing visual stimuli impacts binocular fixation, causing mis-sequencing of visual letters and graphemes with corresponding auditory information. On the other hand, evidence of slow temporal processing of auditory stimuli in DD has led to the *Auditory Processing Deficit Theory* which counter-argues that this miss-sequencing arises not as a result of impairments in visual processing but rather, due to deficits with the delineation of subtle differences in auditory stimuli (Goswami, Power, Lallier, & Facoetti, 2014; Sperling, Lu, Manis, & Seidenberg, 2005; Tallal, Miller, & Fitch, 1995). Another theory proposes that deficits in cerebellar functioning, termed the *Cerebellar Deficit* or *Statistical Learning Deficit Theory* of DD, results in difficulty drawing links between visual and auditory material presented in close proximity to attain automaticity in accessing corresponding representations of both auditory and visual information (Nicolson, Fawcett, Brookes, & Needle, 2010; Nicolson & Fawcett, 1990, 1999, 2011; Nicolson, Fawcett, & Dean, 2001; Ramus & Ahissar, 2012; Swan & Goswami, 1997).

The proponents of causal theories of DD attempt to explore the mechanisms underlying reading difficulties with a particular focus on disruptions to phonological representations. However, a major limitation is that few, if any, are able to articulate the cause of phonological deficits and draw direct links to the range of reading difficulties present in DD samples within a single coherent framework. In addition, not all individuals with DD show consistent deficits across these abilities (Heim et al., 2008; Zoubrinetzky, Bielle, & Valdois, 2014). Therefore, no one single theory has been able to explain all DD cases. Given significant differences in the types of reading difficulties children with DD display, the abundance and diversity of sensory and cognitive theories regarding the cause of DD may actually stem from variability in the reading difficulties exhibited, with different theories applying to different individuals depending on their unique reading profile. Disagreement may also reflect, in part, the limits in our current knowledge regarding how these sensory and cognitive skills support typical reading development, and of the flow on effects that reading acquisition has on the refinement of these abilities. As a result, debate regarding whether these deficits contribute causally to DD, or if they arise instead as a result of limited exposure to text is at the forefront of DD research.

Conclusion

Developmental Dyslexia (DD) is characterised by an unexplained difficulty in a child's ability to decode text. However, despite the specificity of core reading problems, there is ongoing debate regarding suitable diagnostic criteria and clinical classifications used to define the disorder. Reading acquisition results from a dynamic relationship between environmental factors (reading experience and explicit instruction) as well as an individual's biology (neuroanatomical networks subserving linguistic, cognitive and perceptual skills), all of which contribute to the complexity of delineating the causal factors and outcomes of DD.

A prominent theory of DD stems from evidence that visual attention is impaired in individuals with DD. The following chapters will describe attention in DD and consider whether attentional deficits contribute to or arise as a result of reading difficulties. Given considerable heterogeneity of reading difficulties in DD, the importance of individual variability using the DRM will be examined in the hopes of better understanding how attention may differ on the basis of reading profile in DD.

CHAPTER TWO: THE IMPORTANCE OF ATTENTION FOR READING

Being able to focus on and take in visual material whilst excluding irrelevant information is integral for isolating the relevant components of text for translation into sound. Adequate command of visual attention is therefore critical to reading. Despite this, the relevance of visual attention in the context of DD has generally been overlooked. An assumption of most theories of reading development has been that learners move through a slow, attention demanding process initially whereby early word identification and phonological retrieval is labored and effortful. With repeated exposure and practice however, this is thought to progress towards a more automatic process in which words are read fluently and with ease. Accordingly, accessing phonological information swiftly becomes automated and thus does not require much, if any, attentional resources (Gronau & Frost, 1997; Lukatela & Turvey, 1994; Luo, Johnson, & Gallo, 1998; Perfetti, Bell, & Laney, 1988). However, recent evidence suggests that attention is paramount to both sublexical and lexical reading routes, even in cases of automaticity (Besner, Risko, & Sklair, 2005; McCann, Folk, & Johnston, 1992; Reynolds & Besner, 2006) and that the relationship between attention and the segmentation of text varies according to word characteristics (Grainger & Ziegler, 2011; Vidyasagar & Pammer, 1999). Together, these findings have led researchers to consider the specific role attention plays in cases of both typical and atypical reading development.

This chapter first presents an overview of key theoretical models of attention, followed by a discussion of the importance of attention for reading in a typical context. This provides the background for subsequent chapters exploring attention deficits specific to DD.

Models of Attention

It is largely accepted that attention involves maintaining optimal levels of alertness, selecting the most relevant information from a large array of sensory stimuli and suppressing irrelevant information in the environment (Posner & Petersen, 1990). Several theoretical models of attention have been proposed, including those put forward by Corbetta & Shulman (2002) and Posner & Petersen (1990), which share key features. For instance, both agree that attention involves the coordination of both top-down, cognitively-driven processes, as well as bottom-up, sensory-driven processes, and that these interact to determine where attention is directed and what information receives the privilege of processing (Corbetta & Shulman, 2002).

Corbetta and Shulman's ventral and dorsal networks.

According to Corbetta and Shulman (2002), these processes are conceptualised as two distinct but interconnected networks; the *dorsal attention network* and the *ventral attention network*. The dorsal attention network facilitates top-down selection of a stimulus based on its location and features. It is bilaterally supported by the dorsal parietal cortex (i.e., the medial intraparietal sulcus and superior parietal lobule) and the dorsal frontal cortex (i.e., frontal and supplementary eye fields; Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002, 2011). This network is activated when an individual is anticipating a stimulus and voluntarily directs attention to a particular area or towards specific stimulus features to provide an appropriate response. Accordingly, it is thought to reflect strategic factors such as prior knowledge and expectations regarding forthcoming actions. To explain this system, the metaphor of a spotlight is often used, reflecting the idea that meaningful selection occurs as a result of pin-pointed and targeted focus, with a reduction in processing of information outside of the attentional spotlight (Posner & Presti, 1987). The ventral attention network on the other hand is involved in monitoring the environment to detect salient stimuli that are unexpected but behaviourally relevant (Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002, 2011). Neuroanatomically, the ventral network is largely lateralised to the right hemisphere and is supported by the temporoparietal junction (i.e., aspects of the posterior superior temporal sulcus and gyrus, and ventral portion of the supramarginal gyrus) as well as the ventral frontal cortex (i.e., middle and inferior frontal gyrus). When highly salient stimuli are detected, this network assists with breaking current fixation and reorienting attention for processing, analogous to a circuit breaker (Gazzaniga, Ivry, & Mangun, 2009). See Figure 3 for an illustration of the major brain regions associated with dorsal and ventral attention networks.

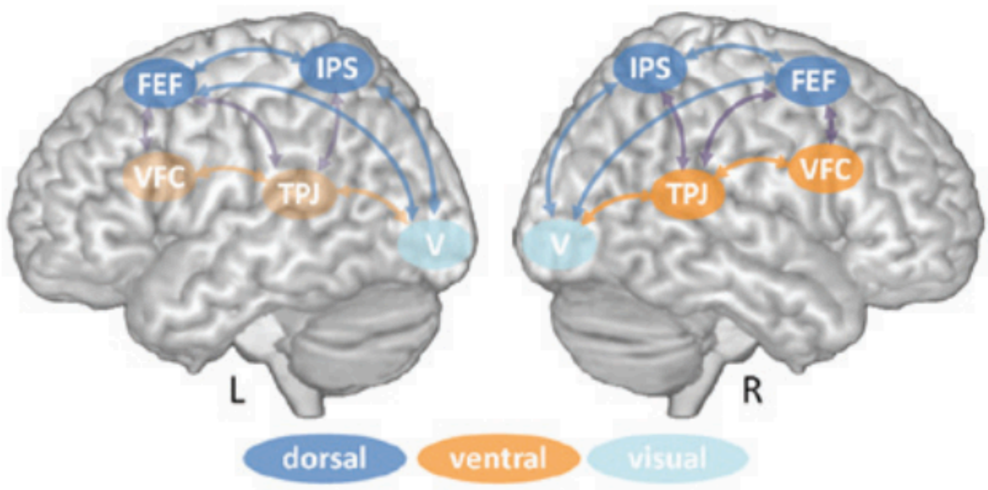

Figure 3. Illustration of the dorsal (dark blue) and ventral (orange) attention networks as well as visual regions (light blue) across left and right hemispheres in the brain according to Corbetta and Shulman (2002). FEF = Frontal Eye Fields; IPS = Intraparietal Sulcus; VFC = Ventral Frontal Cortex; TPJ = Temporoparietal Junction; V = Visual Cortex. Figure taken from Vossel, Geng, & Fink’s (2014) review article.

Posner and Peterson's alerting, orienting and executive networks.

A second leading model proposed by Posner and Petersen (1990) conceptualises attention as comprising three main networks: *alerting*, *orienting*, and *executive*. The alerting network is concerned with maintaining an optimal level of sensitivity to incoming stimuli. It is primarily modulated by norepinephrine involving the locus coeruleus within right frontal and parietal regions (Posner & Rothbart, 2007), mirroring the same functions of the ventral attention network. The orienting network, on the other hand, facilitates the selection of visual information. It is supported by the superior parietal cortex, temporo-parietal junction, frontal eye fields, and superior colliculus, and is primarily modulated by acetylcholine (Posner & Rothbart, 2007). This network relies on several sub-processes including attentional disengagement, shifting, and target re-engagement, sharing similarities with both ventral and dorsal networks in Corbetta and Shulman's model. Finally, the executive attention network involves monitoring and resolving conflict between competing stimuli. It is modulated by dopamine and involves the anterior cingulate gyrus, lateral ventral cortex, prefrontal areas and basal ganglia. As the executive network relies heavily on top-down attentional processes, it has close links to the dorsal attention network. See Figure 4 for an illustration of the anatomy of the attentional networks as proposed by Posner and Peterson (1990).

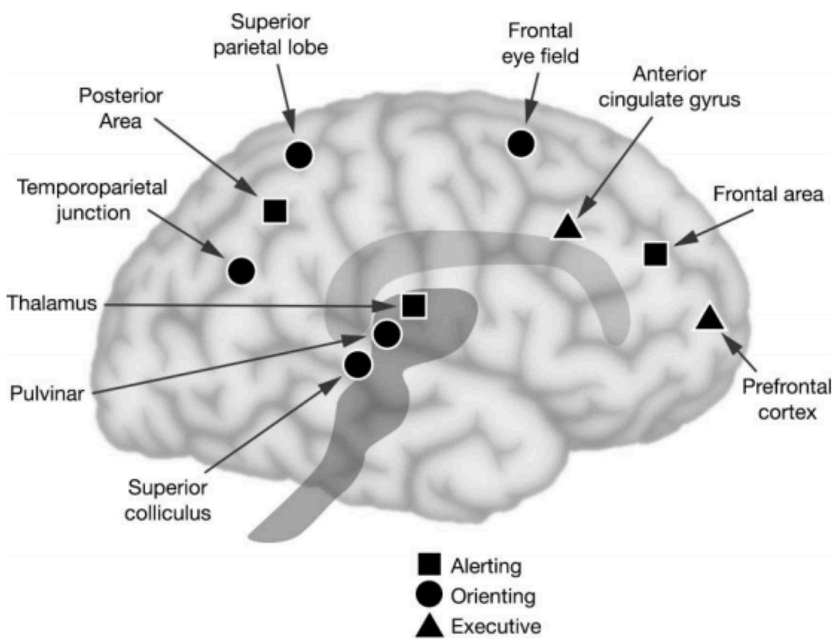

Figure 4. An illustration of the anatomy of the three attentional networks (alerting, orienting, and executive) in the brain as depicted by Posner & Rothbart (2007).

The Link Between Attention and Reading

The link between reading and attention first came from the observation that attention disorders and reading disorders are often reported to co-occur (August & Garfinkel, 1990; Semrud-Clikeman et al., 1992; Snider, 1997; Willcutt & Pennington, 2000). Attention needs to be engaged at the location of the written word before a saccade can be made to that location (Clark, 1999). Thus, as Hoffman & Subramaniam (1995) demonstrate, spatial attention is a crucial mechanism in generating voluntary saccadic movements across text. Accordingly, reading is thought to require at least five key attentional processes; 1) covertly directing focus along the line of text toward a specific area of the visual field, 2) modifying saccadic eye movements in order to focus on a specific grapheme/word, 3) inhibiting adjacent graphemes/words that are irrelevant to current processing, 4) maintaining focus on a grapheme/word for a sufficient period to allow for further cognitive processing, and 5) disengaging attention from one point in the text to move and anchor attention at the next point in the sequence (Clark, 1999; Vidyasagar, 2013). There is substantial evidence demonstrating a positive relationship between individual performances on tasks of attention and reading ability. For instance, children who demonstrate reading skills at or above the expected level for their age have been shown to be better able to use spatial cues to direct their attention towards visual targets efficiently compared with children who read below age-expected levels (Kinsey, Rose, Hansen, Richardson, & Stein, 2004). Further, the amount of visual material held in short term memory stores has been shown to predict variations in reading for typically developing children across Grades 1, 3 and 5 in primary school, independently of phonological awareness, with those who can store greater information going on to become superior readers (Bosse & Valdois, 2009). Poorer readers on the other hand, demonstrate associated difficulties in isolating target letters from distractors in typical visual search paradigms (Casco & Prunetti, 1996; Casco, Tressoldi, & Dellantonio, 1998; Williams, May, Solman, & Zhou, 1995). In addition, reading difficulties are commonly reported in samples of children with behavioural attention deficits (e.g., ADHD; August & Garfinkel (1990) and damage to the posterior parietal cortex resulting in *hemispatial attentional neglect*, has been shown to also result in acquired reading disorders (Shallice & Warrington, 1977). There is also more recent research that demonstrates a neuroanatomical link between reading and attentional control networks with overlap between the bilateral activation of middle cingulate, insular and inferior frontal gyrus in the right hemisphere correlating to both attentional and reading performance (Arrington et al., 2019).

Despite these links, the precise nature of the relationship between attention and reading is still unclear. While a positive correlation between reading and attention performance is consistently reported, this does not speak to the causal nature of the relationship. For instance, it may be that better readers have more practice at processing reading material and are therefore better at selecting letters amongst a background of similar stimuli compared with poorer readers. Alternatively, they may be more efficient at isolating letters from the outset, which promotes rapid gains in reading acquisition making them better readers. There is however, some evidence that attention skills measured prior to the onset of reading are predictive of later reading performance (Carroll, Solity, & Shapiro, 2016). One such example has found that kindergarten children who perform poorly on visual attention tasks subsequently become the poorest readers at school age follow-up in a longitudinal study of 96 typically developing children (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012), suggesting that efficient visual attention skills may be precursors to successful reading acquisition.

Conclusion

There is evidence demonstrating an important link between attention and reading for both good and poor readers. However, the direction of this relationship remains unclear. Knowing the nature of the relationship between reading and attention may provide important insight into the potential cause of disruption to reading acquisition for children with DD and could highlight suitable targets for remediation. The following chapter will explore specific deficits in attention observed in DD samples, emphasising issues regarding heterogeneity and directionality which are central to this thesis.

CHAPTER THREE: ATTENTION IN DEVELOPMENTAL DYSLEXIA

There is a growing body of literature describing DD samples who perform poorly on a wide range of attention measures, lending weight to *Attention Deficit Theories* of DD. Compared with other theories, a noteworthy strength of attention deficit theories is that they often tie together a range of deficits commonly described in the DD literature. For instance, the link between a visual attention deficit and a magnocellular deficit can be made by considering that the anatomical projection of the magnocellular system is to the posterior parietal cortex via the dorsal processing route, an area dominated by magnocellular-like properties such as sensitivity to direction of movement and involved in the direction of gaze (Luiten, Gaykema, Traber, & Spencer, 1987; Stein & Walsh, 1997). In addition, some authors argue that deficits in contrast sensitivity, originally thought to reflect magnocellular dysfunction, can be explained in terms of inattention and inefficient integration of visual material at later stages of perceptual processing (Stuart, McAnally, & Castles, 2001). Attention deficit theories proposing disrupted temporal processing also provide a possible mechanism through which visual information may be misaligned with auditory stimuli, putting forward a potential explanation for aberrant phonological representations in DD (Vidyasagar, 2004).

At present, research regarding attention in DD has focused efforts in two main areas; the overlap between behavioural attention deficits more commonly associated with ADHD, and evidence of cognitive attention deficits, primarily in visual attention span and visuospatial attention functions. This chapter provides an overview of this literature, with an emphasis on the variability in attention deficits reported in DD samples. The role that individual reading profile may play in explaining this variability is then considered, providing the impetus for the methodology adopted in subsequent empirical chapters.

Attention Deficits in DD

Behavioural attention deficits in DD.

Along with characteristic difficulties in decoding text, children with DD are commonly described as presenting with a range of attentional deficits that manifest behaviourally. These are often measured using behavioural rating scales completed by either a caregiver, teacher, or the child themselves. For instance, Dahle and Knivsberg (2013) describe a sample of 70 children with a sole diagnosis of DD who were rated by both parents and teachers as having significantly more behavioural problems than their same-age peers, with at least half demonstrating attention problems at or above clinical cut-offs. Difficulties included maintaining focus on tasks, an inability to sit still, appearing to day-dream and trouble taking in multi-step instructions. Interestingly, self-report measures from this group also indicated higher levels of attention-related problems demonstrating that children with DD themselves displayed insight into their own attention deficits.

As noted in Chapter 1, there is considerable overlap between DD and symptoms of ADHD, with at least 20-40% of children with a primary diagnosis of DD experiencing inattentive and/or hyperactive/impulsive symptoms at, or above, clinical cut-offs (Dykman & Ackerman, 1991; Gilger et al., 1992; Semrud-Clikeman et al., 1992). As is the case with many developmental disorders however, the nature and severity of co-occurring ADHD symptoms vary across children with DD, making diagnosis and treatment challenging. Although some experience mild symptoms of ADHD that fall below what is required for a comorbid diagnosis, many more exhibit symptoms that are significant enough to warrant clinical concern, but do not receive appropriate treatment (Denckla, 1993). Some researchers describe the overlap between DD and symptoms of ADHD as arising due to the additive effects of possibly having both disorders independently (Pisecco, Baker, Silva, & Brooke, 2001; Swanson, Mink, &

Bocian, 1999), while others have suggested a unique comorbid subtype exists. For instance, Rucklidge and Tannock (2002) observed significantly poorer performance on rapid naming tasks in adolescents with symptoms of both DD and ADHD than those with either ADHD or DD alone. The authors suggest that poor rapid naming may therefore represent a key differentiating factor for the combined phenotype and a potential marker for increased risk of co-occurring ADHD symptoms in DD. An alternative view is that symptoms consistent with ADHD also form part of the core DD profile in that they co-occur with reading difficulties, reflecting common vulnerabilities (Pennington, 2006). One significant difficulty, however, is determining whether behavioural attention deficits in DD samples are actually the result of reading difficulties, or if they contribute uniquely to DD. For instance, children who struggle to read may appear inattentive in that they disengage from reading activities, especially in the school setting (Marzocchi, Ornaghi, & Barboglio, 2009). On the other hand, children with difficulties maintaining focus will miss important teaching instruction required for reading acquisition and are therefore more likely to become poorer readers.

Cognitive Attention Deficits in DD.

Visual attention span deficits in DD.

In addition to poorer ratings on behavioural measures of attention, studies have reported reduced performance on cognitive measures of visual attention in children with DD. Of particular interest is *visual attentional span*. Visual attention span is defined as the number of individual elements that can be correctly recalled after simultaneous presentation of visual stimuli within a given, often very brief, time window (Lobier, Zoubrinetzky, & Valdois, 2012). It is traditionally measured using cognitive paradigms that present horizontal multi-element arrays of visual stimuli (commonly letters) to the participant, requiring them to report either all (whole-report) or some of the items they can recall based on pre-determined features such as colour (partial-report). More contemporary tools such as the Theory of Visual Attention (TVA) paradigm have incorporated both top-down and bottom-up components of visual attention into complex mathematical models allowing for estimation of visual attention span on an individual basis.

Evidence of reduced visual attention span has been reported in many DD samples (Bosse, Tainturier, & Valdois, 2007; Dubois et al., 2010; Hawelka & Wimmer, 2005; Jones, Branigan & Kelly, 2008; Pammer, Lavis, Hansen, & Cornelissen, 2004; Romani, Tsouknida, di Betta, & Olson, 2011; Valdois et al., 2003) leading to a *Visual Attention Span Deficit Theory* of DD. Reduced visual attention span in DD samples is thought to reflect deficits in allocating and sustaining attention across multi-element arrays due to deficiencies in ventral or alerting attention networks, thereby limiting the number of visual items that can be processed in parallel (Bosse et al., 2007; Stenneken et al., 2011). Reduced visual attention span has been reported in both children and adults with DD across languages including French (Bosse & Valdois, 2009; Bosse et al., 2007) Portuguese (Fernandes, Vale, Martins, Morais, & Kolinsky, 2014) and English (Romani et al., 2011), and has been shown to be limited to the basic visual processing of stimuli rather than represent an inability to successfully match visual stimuli to corresponding phonological codes within the mental lexicon (Lobier et al., 2012; Romani et al., 2011). Accordingly, studies have found that reduced visual attention span is independent of phonological problems for a number of poor readers suggesting an integral role in both typical and atypical reading development (Bosse & Valdois, 2009; Prado, Dubois, & Valdois, 2007). It can also differentiate between good and poor readers in non-clinical samples (Bosse & Valdois, 2009). Crucially, findings from Bosse and Valdois (2003) as well as Chen, Zheng and Ho (2019) demonstrate that restricted visual attention span in DD samples is evident even after accounting for reduced reading ability, indicating that reduced visual attention span may be contributing to reading dysfunction in DD. Furthermore, atypical eye movements commonly reported in those with DD, such as significantly greater rightward fixations (Rayner, 1998), have also been explained by reduced visual attention span. For instance, Prado and colleagues (2007) describe increased oculomotor shifting as an attempt to increase diminished visual attention span capacities during tasks requiring global, rather than local processing of information.

From an anatomical perspective, reduced visual attention span has been associated with poorer superior parietal activation (Peyrin, Démonet, N'Guyen-Morel, Bas, & Valdois, 2011; Peyrin et al., 2012), leading to the hypothesis that parietal abnormalities are specifically responsible for visual attention span deficits in DD. Indeed, administration of a targeted intervention program to improve visual attention span in a DD sample has been shown to increase bilateral activation of the superior parietal lobes, which, in turn, resulted in both improved visual attention span and reading performance (Valdois et al., 2014). However, the superior parietal lobe has also been linked to other attentional capacities implicated in DD including visuospatial attention (Behrmann, Geng, & Shomstein, 2004; Corbetta & Shulman, 2002; Mitchell & Cusack, 2008; Scalf & Beck, 2010; Wojciulik & Kanwisher, 1999; Xu & Chun, 2009). Therefore, evidence of reading improvements and subsequent increases in parietal activity following these interventions may index improvements in attention more broadly.

Despite evidence of visual attention span deficits in DD, consensus regarding the specific mechanisms that underpin poor performance remains elusive. Visual attention span can be influenced by several attentional and cognitive underlying mechanisms. As such, reduced span may have multiple contributory processes. For instance, an individual with DD may have lower stimulus detection thresholds, be slower to process visual material, struggle to inhibit irrelevant stimuli, allocate attention inefficiently across space or demonstrate a core reduction in their short-term capacity which could all result in poorer performance on tasks assessing visual attention span. In fact, some researchers argue that reduced visual attention span in DD is a by-product of the effects of increased vulnerability to *crowding* due to poor top-down inhibitory control, rather than being reflective of core storage-related deficits (Cassim, Talcott, & Moores, 2014). Support for this notion comes from findings that poor readers struggle to identify relevant stimuli amongst a set of distractors (Casco, Tressoldi, & Dellantonio, 1998; Ruddock, 1991; Vidyasagar & Pammer, 1999), as well as poor performance on tasks requiring identification of stimuli flanked by alternatives even after being cued to their location (Moores, Cassim, & Talcott, 2011). In terms of reading, susceptibility to crowding may account for anecdotal reports of 'mixing' of letters in those with DD as well as slow reading rates (Geiger, Lettvin, & Fahle, 1994; Rayner, Murphy, Henderson, & Pollatsek, 1989). Adding weight to the crowding argument, rehabilitative techniques that adjust letter spacing to reduce crowding interference have been shown to contribute to improvements in those with DD even when compared to reading matched counterparts (Perea, Panadero, Moret-Tatay, & Gómez, 2012; Spinelli, Luca, Judica, & Zoccolotti, 2002), although it does not provide complete remediation (Martelli, Filippo, Spinelli, & Zoccolotti, 2009; Zorzi et al., 2012).

Reduced visual attention span in DD can also be explained in terms of a difficulty to focus attentional resources in the centre of gaze due to a more diffuse attentional window or mis-allocation based on stimuli location (Facoetti, Paganoni, & Lorusso, 2000). In addition, there is evidence suggesting that individuals with DD require longer exposure durations of stimuli to perform at levels equivalent to their peers, and that by extending the presentation window they are then better able to discriminate targets from distractors on visual attention span tasks (Hawelka, Huber, & Wimmer, 2006). Furthermore, there is substantial evidence that reduced visual attention span may index reduced speed of processing in both child and adult

DD samples (Bogon, Finke, Schulte-Körne, et al., 2014; Dubois et al., 2010; Stenneken et al., 2011).

Purist accounts of visual attention view visual attention span functions as stimulus-general (Lobier et al., 2012; Romani et al., 2011). Accordingly, if the proposed reading deficit in DD is a result of impaired visual attention span capacity, researchers have argued it should affect letters and non-letters alike. Unfortunately, most studies in this area have not compared visual attention performance using a range of stimuli that do not rely on a degree of linguistic processing. Of those that have, some report comparable deficits across stimuli supporting a global visual attention span deficit in DD (Lobier, Dubois, & Valdois, 2013; Sieroff & Posner, 1988), whereas others have not observed the same pattern (Collis, Kohnen, & Kinoshita, 2012; Hawelka & Wimmer, 2008; Shovman & Ahissar, 2006; Valdois, Lassus-Sangosse, & Lobier, 2012; Yeari, Isser, & Schiff, 2017; Ziegler, Pech-Georgel, Dufau, & Grainger, 2010), casting doubt on the generalisability of visual attention span deficits in DD.

Visual attention span measures traditionally involve participants verbally reporting stimuli under time constraints. This approach requires rapid access to phonology, a skill known to be impaired in DD (Di Filippo, Zoccolotti, & Ziegler, 2008; Jones, Branigan, & Kelly, 2009; Katzir et al., 2006). Increased latencies or reduced accuracy on visual attention span tasks may therefore reflect difficulty accessing and/or producing phonological information for linguistic stimuli specifically, rather than an exclusive reduction in visual attention span capacity. Together, these issues plague the visual attention span literature of DD and as a result, debate continues regarding the ability of visual attention span deficits to explain DD uniquely.

Visuospatial attention deficits in DD.

As reading involves shifting attention rapidly along sequentially presented letters and words (Vidyasagar & Pammer, 1999), studies have also examined the importance of *visuospatial attention* in DD. Visuospatial attention refers to the selection of information for further processing based on its location in space (Vecera & Rizzo, 2006), requiring continual disengagement and re-engagement of focus to accommodate new stimuli (Corbetta et al., 2008). According to the *Sluggish Attentional Shift Theory* of DD, individuals with DD struggle to process letter and word sequences as they are unable to disengage fast enough from one item to move to the next (Brannan & Williams, 1987; Facoetti, Lorusso, Paganoni, Cattaneo, Galli, & Mascetti, 2003; Hari, Valta, & Uutela, 1999; Hari, Renvall, & Tanskanen, 2001; Lallier, Donnadieu, Berger, & Valdois, 2010; Lallier, Tainturier, et al., 2010). For instance, individuals with DD demonstrate attentional dwell times 30% longer than normal readers (Hari et al., 1999) and abnormal cortical processing of rapidly presented stimuli (Lallier, Tainturier, et al., 2010). The *attentional blink* refers to the lag in sensory processing that occurs after identifying a target stimulus. For the most part, following stimulus processing, individuals are 'blind' to successive stimuli presented within 400-600 milliseconds, however those with DD have been shown to require longer inter-trial intermissions to reach performance equivalent to peers (Duncan, Ward, & Shapiro, 1994). Additional support for this comes from evidence of reduced performance in the reorienting, but not initial orienting, of attention compared with both age matched and reading matched controls (Fu, Zhao, Ding, & Wang, 2019). As a result, individuals with DD are thought to possess an underlying spatial cueing deficit reflecting inefficiencies within the reorienting attention network of Posner and Peterson's model of attention, causing difficulty rapidly shifting attention away from processed words or word segments towards others when reading (Facoetti, Lorusso, Paganoni, Cattaneo, Galli, Umiltà, et al., 2003; Facoetti, Paganoni, & Lorusso, 2000; Facoetti et al., 2006; Goldfarb & Shaul, 2013; Proulx & Elmasry, 2014; Ruffino et al., 2010). Interestingly, despite high comorbidity rates with ADHD, longer attentional blinks and difficulty processing rapidly changing visual displays are specifically reported in those with DD but not with ADHD, highlighting the unique involvement of shifting attention for reading (Laasonen et al., 2012).

Despite this evidence, not all studies report significant group differences between DD and control groups on measures of temporal lag (McLean, Stuart, Coltheart, & Castles, 2011). Some suggest that longer attentional blinks are instead the result of broader processing speed impairments (McLean et al., 2011), or a primary sensory encoding deficit (Skottun, 2000), with many authors failing to control for baseline sensitivity to stimuli before testing (Badcock, Hogben, & Fletcher, 2008). Although individuals with DD demonstrate initial performance impairments, improvement in the identification of stimuli presented in close succession is often reported over extended trials, with differences compared with controls not evident when comparing rates of improvement (Badcock, Hogben, & Fletcher, 2011). Rehabilitative techniques such as the use of action video games have also been shown to diminish the time required to recover from an attentional blink in those with DD, with flow on improvements in reading speed (Franceschini et al., 2013, 2017; Gori et al., 2013). Interestingly, similar improvements in performance have been reported with increasing age and cognitive growth throughout typical development (Dye & Bavelier, 2010). Together these findings suggest that expected development of attentional abilities may be dysfunctional in DD yet with appropriate intervention, they can be ameliorated to facilitate subsequent improvements in reading.

In addition to an overall sluggish attentional shift, individuals with DD have been shown to allocate attentional resources across visual fields differently to controls. In neurologically typical individuals, decades of research demonstrate a systematic bias, or asymmetry, in the processing of information across space, with a slight advantage for information presented in left visual fields over that presented in the right (Jewell & McCourt, 2000; Voyer, Voyer, & Tramonte, 2012). In line with the contemporary model of attention put forth by Corbetta and Shulman (2002) that argues for hemispheric lateralisation of the ventral attention network, greater anatomical volumes of associated structures in the right hemispheres of healthy individuals has been shown to be correlated with larger leftward biases on behavioural line bisection tasks (de Schotten et al., 2011). This phenomenon, known as *pseudoneglect* (Voyer et al., 2012), is not present in a number of clinical groups including those with DD as well as, with greater severity, those with acquired neglect (Bellgrove, Eramudugolla, Newman, Vance, & Mattingley, 2013; Sheppard, Bradshaw, Mattingley, & Lee, 1999; Facoetti, Lorusso, Paganoni, Cattaneo, Galli, & Mascetti, 2003; Facoetti et al., 2006; Malone, Kershner, & Swanson, 1994). Research suggests that individuals with DD show either an absence of the slight leftward preference typical of pseudoneglect (Facoetti, Paganoni, & Lorusso, 2000; Polikoff, Evans, & Legg, 1995; Sireteanu, Goertz, Bachert, & Wandert, 2005; Waldie & Hausmann, 2010), or an inability to suppress stimuli presented in the right visual field in combination with a significant inability to process stimuli in the left visual field, effectively deemed a form of mini-neglect (Facoetti, Lorusso, Paganoni, Cattaneo, Galli, Umiltà, et al., 2003; Facoetti & Molteni, 2001; Facoetti, Turatto, Lorusso, & Mascetti, 2001; Facoetti et al., 2006; Geiger et al., 1994; Hari et al., 2001; Rayner et al., 1989; Ruffino et al., 2010; Valdois, Gérard, Vanault, & Dugas, 1995). Several studies have demonstrated, using cognitive paradigms and imaging techniques, the presence of a right-sided advantage for the processing of words or stimuli in those with DD (Eden, Stein, & Wood, 1993; Facoetti, Turatto, Lorusso, & Mascetti, 2001; Friedmann, Kerbel, & Shvimer, 2010; Illingworth & Bishop, 2009; Valdois et al., 2011; Valdois, Bosse, & Tainturier, 2004; Valdois et al., 2003). This has been argued to reflect the abnormal exogenous control of spatial attention across hemispheres associated with under-development of parietal attentional networks (for a review see Liu, Liu, Pan & Zu, 2018). Furthermore, individuals with DD are also consistently shown to have difficulties engaging with peripheral stimuli, with many recording significantly slower detection of targets in extremities of the visual field requiring endogenous orienting, especially following the presentation of central targets (Buchholz & Davies, 2005; Facoetti & Molteni, 2001). As a result, a *Visuospatial Deficit Theory* of DD has been proposed. According to this theory, excessive inhibition of words and letters in the left hemifield, together with over-distractibility of those in the right, can result in a number of errors when trying to decode text (Vidyasagar & Pammer, 2010). This suggests that children with deficits in attentional allocation fail to attain accurate letter to sound mappings resulting in subsequent difficulties reading.

In general, individuals with DD display a range of deficits in orienting attention across space, however, much like studies assessing visual attention span, the findings are mixed. As a result, there is little understanding regarding what underlies poor visuospatial performance and how these deficits are directly linked to the reading difficulties that individuals with DD display.

Linking Attention and Reading Profile in DD

Despite significant evidence of attention deficits reported in DD cohorts, not all individuals present with a consistent pattern of poor performance (Lukov et al., 2015). Given this variability, researchers have sought to better understand how these mixed findings may be influenced by, or reflected in, the type of reading difficulties an individual with DD presents with (i.e., their reading profile). Bakker and colleagues pioneered initial investigations into how visual attention varied across individuals with DD (Bakker, 1992). Observations from several psychophysiological studies noted a shift in the activity of the hemispheres from right to left during reading acquisition, coinciding with a progression from more laboured and effortful reading to more automated output. This led Bakker to conclude that DD may arise as a result of dysfunctional lateralisation of attention networks (Bakker, Bouma, & Gardien, 1990; Jonkman, Licht, Bakker, & den Broek-Sandmann, 1992; Licht, Bakker, Kok, & Bouma, 1988). He suggested that some children with DD fail to make the shift from right to left, thus perseverating in a solely visual analysis of written material, which he referred to as *P-type dyslexia*. Other children with DD make this shift prematurely, when visual recognition of words has not yet become sufficiently automated, which Bakker referred to as *L-type dyslexia*. These children try to process information by means of predominant semantic and syntactic strategies, thus showing an anticipatory or 'guessing' reading style. According to Bakker, P-type and L-type dyslexics could be distinguished on the basis of their differential reading speed and the type of errors made. Slow reading speed and time-consuming errors (e.g., self-corrections, syllabic reading, fragmentations, stuttering, and repetitions) was specific to P-types, whereas relatively fast reading but substantive errors (e.g., omissions, substitutions and inversions) was typical of L-types (Lorusso, Facoetti, & Molteni, 2004). Additional research then suggested the existence of a third group of DD, the so-called *M-type dyslexics* (mixed type). M-types are described as reading rather slowly but also making both time-consuming and substantive errors (Masutto, Bravar, & Fabbro, 1994). However, since Bakker's research, the notion that individuals with DD differ in the involvement of left and right hemispheres has been contradicted by studies using more contemporary behavioural, cognitive and electrophysiological measures, and there has been little evidence to suggest that these initially proposed subtypes of DD exist (Fabbro et al., 2001; Jonkman et al., 1992).

More recent attempts to understand the variability in attention deficits observed in DD have instead drawn links between attention and the two routes of reading proposed by the Dual Route Model. The *Multi-Trace Memory* (MTM) model suggests the existence of two attention procedures associated with word reading, a *global* and an *analytic* process (Bosse et al., 2007; Dubois et al., 2010; Hawelka & Wimmer, 2005; Jones, Branigan, & Kelly, 2008; Pammer, Lavis, Hansen, & Cornelissen, 2004; Romani, Tsouknida, di Betta, & Olson, 2011; Valdois et al., 2003). Global and analytic reading procedures differ in the size of the attentional window required to extract information from text successfully. In the global procedure, the window extends over the entire letter string. In contrast, the analytic procedure is restricted to the first part of the orthographic sequence (typically a syllable) and then moves sequentially until the entire word has been processed. At each step, phonological information is accessed and held within a phonological buffer so that the entire sequence is available at the end of processing. The MTM model can be linked to the DRM, by proposing that attentional deficits of differing severities across global and analytic processes can affect reading acquisition and result in various profiles of DD. For instance, deficits in analytical processing such as sluggish attentional shifting disturbs access to processing individual graphemes in quick succession, thereby resulting in problems engaging sublexical reading strategies (Facoetti et al., 2006; Franceschini et al., 2012). On the other hand, an inability to extend the attentional window over the whole sequence of a word due to reduced visual attention span prevents reading in the global mode and would thus impact more on lexical reading, especially in English where irregular words require simultaneous processing of long, multi-letter graphemes for successful production (Franceschini et al., 2013, 2017; Gori et al., 2013).

In line with this, research has demonstrated that the presence of visuospatial deficits (i.e., left mini-neglect and right over-distractibility) may in fact be specific to sublexical DD. For instance, Facoetti and colleagues (2006) studied children whose DD was categorised by impaired nonword reading (sublexical DD), those with intact nonword reading (lexical DD), and an age matched comparison group. They showed that children with lexical DD and typical readers performed comparably on a cued detection task, whereas those with poor nonword reading specifically (sublexical dyslexics) showed reduced inhibition for targets in un-cued locations, particularly in the right visual field. They further demonstrated that children with sublexical DD recorded slower time courses for processing of both visual and auditory stimuli compared with both age and reading matched controls, as well as other DD participants with intact nonword processing. Similar findings have been reported for attentional masking paradigms whereby DD individuals with specific sublexical deficits have been shown not only to take longer to respond and recover following masking of stimulus, but to also display a more pronounced atypical laterality in attention towards the right hemifield (Ruffino et al., 2010). In fact, the longitudinal study by Franceschini and colleagues (2012; see the 'link between visual attention and reading' section in chapter two) demonstrated that spatial cueing problems were more pronounced in children with specific nonword impairments (sublexical DD). These findings have been discussed in light of computational and neurobiological models that propose attentional engagement (subserved by the ventral attentional network) is specifically involved in the sublexical spelling-to-sound mappings (Downar, Crawley, Mikulis, & Davis, 2000). Phonological assembly requires a grapheme parsing process, which is the segmentation of a letter string into its constituent letter parts (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Accordingly, difficulties in drawing out and blending together graphemes due to dysfunctional allocation of attention across space may result in greater deficits in reading nonwords due to their stronger reliance on serial processing. Indeed, studies have demonstrated that in cases of acquired attentional neglect, previously typical readers made more errors on the contralesional side of nonwords compared with regular words (Sieroff & Posner, 1988). Even typical adult readers are more inaccurate when reporting the letters for nonwords compared with regular words following manipulation of visuospatial attention using spatial cues (Auclair & Siéroff, 2002). Crucially, patients with severe attentional neglect still show preserved lexical processing when reading (Làdavas, Shallice, & Zanella, 1997) suggesting that visuospatial attention deficits may contribute to specific difficulties in sublexical but not lexical processing.

Researchers have also demonstrated that a reduction in the size of the attentional window bears more impact on global compared with analytic reading processes and, by extension, the successful reading of irregular words stored in the lexicon (Ans, Carbonnel, & Valdois, 1998). For example, Bosse and colleagues (2003, 2007) report reduced visual attention span groups of children with DD with intact phonological skills compared with reading matched controls. Lassus-Sangosse, N'guyen-Morel and Valdois (2008) observed that children with DD without specific phonological deficits exhibited a simultaneous processing disorder whereby accuracy in the report of letter strings was significantly reduced compared with other poor readers with predominant phonological problems. This is thought to be because the attentional window is reduced too much and irregular words can no longer be processed as wholes to generate their respective phonological codes in one step. Subsequently, individuals attempt to read these words by sounding them out sequentially via the sublexical route, resulting in inaccurate output. However, these results need to be interpreted with caution as there is disagreement as to whether reductions in the size of the attentional window actually reflects reduced span, or if it can be accounted for by a substantial tendency for rightward fixations in text reading that could explain deficits in both lexical and sublexical processing (Liddle, Jackson, Rorden, & Jackson, 2009).

While there is growing evidence supporting the MTM approach to reading, there is debate regarding the precise mechanisms that drive attentional modulation within this approach. For instance, questions have been raised regarding how the attentional window 'knows' the degree of modulation required to parse words successfully. As it stands, the model does not yet describe the degree of initial processing that would be required to determine the regularity and familiarity of a word to then govern which attentional approach to undertake. Whether attention operates globally first, with more localised focus being directed only after initial word identification and semantic processing (*late-selection theory*; LaBerge & Samuels, 1974; Sieroff & Posner, 1988), or if analytic processing occurs concurrently, activating before lexical access takes place, or at least before it is fully executed (*early-selection theory*, Auclair & Siéroff, 2002; Behrmann, Moscovitch, & Mozer, 1991; Klein, Behrmann, & Doctor, 1994) continues to be debated. There is also evidence that attention deficits are not always consistently tied to specific DD profile (Lukov et al., 2015) and that individuals with a specific type of DD can present with more than a single type of attention deficit (Ziegler et al., 2008). Regardless, the MTM model provides an attractive approach through which to view the variability of attentional deficits reported in DD cohorts and draws important links to the heterogeneity seen in the reading profiles of those with DD based on the DRM of reading.

Conclusion

A range of behavioural and cognitive attention deficits are commonly reported in DD samples. However, there is significant variability in how these manifest across individuals with DD. This has meant that the role attention may play in DD is not fully understood. Given early links between various aspects of attention and differing components of reading, investigating attention in the context of individual reading profile may help explain the variability seen across DD samples, and could potentially help to identify which children with DD are more vulnerable to co-occurring attentional deficits.

CHAPTER FOUR: THE CURRENT THESIS

At its core, DD is characterised by specific difficulties in reading. However, despite the circumscribed nature of the skills impacted, we are yet to establish consensus regarding its cause. This is, in part, due to considerable heterogeneity in the types of reading difficulties experienced by children with DD, as well as the wide array of additional deficits that they present with. Past research has documented substantial attentional dysfunction both behaviourally and across cognitive measures for individuals with DD. Yet, much like the variation seen in the types of reading difficulties displayed, the nature and severity of attention deficits also differs considerably across individuals with DD.

Addressing the Issue of Directionality

A significant complicating factor in determining causes of DD is that reading is an acquired skill. Accordingly, learning to read not only results in the refinement of important linguistic networks, it also impacts on supplementary sensory and attentional systems that work to support reading acquisition (Chokron & Imbert, 1993; Curtis, 1980; McBride-Chang et al., 2011). Hence, a child who is reading less text will accumulate far less reading experience and, as a result, complimentary reading skills including visual scanning, oculomotor control and visuospatial skills will also be less practiced. Therefore, the presence of attention deficits in children with DD could reflect reduced reading experience and limited opportunity to fine-tune these processes to the same degree as peers, thereby arising secondary to reading difficulties (Huettig, Lachmann, Reis, & Petersson, 2018). Acknowledging this, there is increasing recognition of the value of employing both a traditional age matched control group, as well as a reading matched group in studies of DD (Goswami, 2015). Inclusion of a reading matched group allows individuals with DD to be compared with younger, typically developing readers of equivalent reading ability, thereby accounting for the role reduced reading exposure may play in explaining the findings. Accordingly, if differences are found for the DD group in relation to reading matched counterparts, one can infer that attentional deficits reported for age matched comparisons occur above and beyond poor reading ability. On the other hand, if an attentional deficit is present in both the DD and reading matched group, one could argue that it is reflective of suboptimal reading exposure and poor ability which is associated with a general immaturity of reading networks.

Examining the nature of attention deficits in DD in this way will provide important insights into how they may be contributing to reading difficulties and could explain mixed results reported in the literature. From a theoretical perspective, findings may guide further refinements to developmental models of both reading and attention, describing progress in both typical and atypical circumstances. It is hoped that as a wider consequence, clinicians and educators will be better placed to identify children with DD who are most vulnerable to co-occurring attentional problems, allowing them to allocate resources efficiently and provide necessary support to foster continued learning.

Thesis Objectives

This thesis sought to investigate attention in a 'pure' sample of children with a sole diagnosis of DD. The broad objectives were twofold; 1) to explore the role individual reading profile may play in explaining variability of attention deficits in children with DD, and 2) to clarify the direction of the relationship between attention and reading through comparisons to both age matched and reading matched controls.

To address these two objectives, three studies examining attention using different methods were conducted. The first study investigated reported behavioural symptoms of attention deficits using the Conners 3 parent-rated attention deficit hyperactivity disorder (ADHD) symptom questionnaire (Chapter 5), the second explored the cognitive mechanisms underlying visual attention span deficits through computational modelling on the Theory of Visual Attention (TVA) paradigm (Chapter 6), and the third examined performance on a perceptual decision making task assessing visual motion processing using electroencephalography (Chapter 7).

Although it was expected that children with DD would present with attention deficits compared to their typically developing counterparts, it was hypothesised that performance would vary across the spectrum of reading profiles. Accordingly, children whose DD was characterised by relatively poorer lexical skills were expected to perform differently on measures of attention to those at the other end of the continuum with relatively poorer sublexical skills. Given the novelty of reading matched comparisons design and the shortage of studies adopting this methodology in the literature, it was unclear whether the DD group would continue to perform worse than both sets of controls on attentional measures, once reading ability was considered. As such, it was unknown whether attention deficits would be seen as uniquely contributing to, or arising as a result of, poor reading ability in DD.

CHAPTER FIVE: IDENTIFYING CHILDREN WITH DEVELOPMENTAL DYSLEXIA AT-RISK OF CO-OCCURRING ADHD SYMPTOMS

Preamble

There is increasing awareness of the significant overlap between DD and behavioural symptoms of attention deficits commonly associated with ADHD (Willcutt & Pennington, 2000). However, the nature and severity of ADHD symptoms varies significantly across children with DD. Some children display ADHD-like behaviour significant enough to warrant a formal comorbid diagnosis and many more children experience symptoms that do not meet diagnostic criteria but still affect functioning (Denckla, 1993). Being able to identify which children with DD are most at-risk of experiencing ADHD symptoms is therefore crucial for developing individualised treatment plans and optimising long-term outcomes.

This paper examined children with DD to confirm that they experience significantly greater co-occurring ADHD symptoms than same-age, typically developing peers despite their sole DD diagnosis. It extended this by also examining whether ADHD symptoms occurred even after reading ability was accounted for in comparisons to reading matched controls. Whether there were subgroups of children with DD who were more likely to experience ADHD symptoms based on their reading profile was also investigated.

This is the first study to investigate ADHD symptoms in DD using both age matched and reading matched comparison groups and acknowledge the role that differences in reading profile may play in the overlap between ADHD and DD. It is the first to show that co-occurring ADHD symptoms of inattention and executive dysfunction co-occur in DD even after controlling for reading ability, and that children whose DD is characterised by poorer lexical abilities are more likely to experience these ADHD symptoms. As a commonly used clinical measure of ADHD symptomology (Conners 3 Parent Short Form) was utilised to better understand the behavioural manifestation of attention deficits in DD in this paper, these findings have considerable clinical relevance and can be readily translated into practice. Thus, this study provides a novel way by which clinicians and researchers can identify children with DD at-risk of behavioural attentional problems.

Abstract

Comorbidity between Developmental Dyslexia (DD) and ADHD has been well established but is it not clear whether children with a sole diagnosis of DD experience ADHD symptoms that co-occur with their reading difficulties and which children are more likely to experience these ADHD symptoms. This study examined children with a sole diagnosis of DD to determine whether ADHD symptoms are evident despite these children not being flagged as having attentional difficulties and if they co-occur over and above reading ability. It also aimed to examine whether children with DD who are more likely to experience these symptoms can be identified on the basis of their reading profile (relative lexical and sublexical abilities). Forty-one children with DD only were compared with 24 Age Matched (AM) and 17 Reading Matched (RM) controls on the Conners 3 Parent Short-Form. The DD only group demonstrated higher levels of inattention and hyperactive/impulsive ADHD symptoms as well as more executive functioning, aggression and learning problems than AM controls, but only higher levels of inattentive ADHD symptoms, executive functioning and learning problems than RM controls. Moderation analyses revealed that children with DD whose reading was characterised by relatively poorer lexical abilities had higher levels of inattention ADHD symptoms and executive functioning problems. Results suggest that in children with a sole diagnosis of DD, symptoms of inattention and executive functioning problems co-occur with poor reading, even after reading ability is accounted for, and that children whose DD is characterised by poorer lexical abilities are at risk of experiencing co-occurring ADHD symptoms.

Keywords: Learning Disabilities; Developmental Dyslexia; attention-deficit/hyperactivity disorder; ADHD; Attention; Comorbidity

Introduction

Developmental dyslexia (DD) is a common learning disorder characterised by difficulties in accurate or fluent word recognition and decoding (Lyon, Shaywitz, & Shaywitz, 2003), with a prevalence of 5 to 10% (Shaywitz et al., 1999). While children with DD are diagnosed on the basis of their specific reading difficulties (American Psychological Association, 2013), they can experience a range of cognitive and behavioural difficulties (Menghini, Finzi, Benassi, Bolzani & Facoetti, 2010), highlighting its dimensional nature. In particular, behavioural attentional symptoms characteristic of attention-deficit/hyperactivity disorder (ADHD) have been previously reported in children with DD (Dahle & Knivsberg, 2013; Marzocchi, Ornaghi, & Barboglio, 2009). Despite significant associations between attention and reading difficulties in children with DD only (Willcutt & Pennington, 2000), it remains unclear whether behavioural attention difficulties are inherent with reading difficulties (i.e. characteristic of DD) and therefore co-occur, or are only evident in children with both DD and ADHD independently as a result of high comorbidity (Willcutt & Pennington, 2000). It might be expected that children with DD only who have severe reading difficulties are more likely to experience such symptoms, however this has not yet been tested. Instead, it may be that a child's type of reading difficulties (relative lexical and sublexical abilities) rather than severity is helpful for identifying those children with DD who are likely to experience symptoms of ADHD. Together, this knowledge would help to identify which children with DD are likely to benefit from implementing strategies to reduce behavioural attention difficulties, and alleviate life-long difficulties that affect their psychological well-being, education and future employment outcomes (Mortimore & Crozier, 2006; Prevett, Bell, & Ralph, 2013).

A current requirement for a diagnosis of DD is that reading difficulties are unexpected, occurring in the absence of any other intellectual, neurological or developmental impairments that could explain symptoms, including ADHD (DSM-5: American Psychological Association, 2013). Although DD and ADHD have different characteristic features, and strict application of the diagnostic criteria of DD precludes an ADHD diagnosis, up to 20-40% of children with DD are also diagnosed with ADHD, which is significantly more than expected by chance (Dykman & Ackerman, 1991; Gilger, Pennington, & DeFries, 1992; Semrud-Clikeman et al., 1992; Willcutt & Pennington, 2000). In general, studies have suggested that children with a sole diagnosis of DD exhibit predominant phonological deficits, without attentional or executive difficulties (Ramus, 2003; Snowling, 2000; Stanovich, 1988). In contrast, those with ADHD only display attentional and executive difficulties with age-appropriate reading skills (Marzocchi et al., 2009; Pennington, Grossier, & Welsh, 1993; Purvis & Tannock, 2000; Willcutt et al., 2001; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005). For children and adolescents with comorbid DD and ADHD, however, the study findings are less clear. Some researchers have described additive effects of both disorders (Pisecco, Baker, Silva, & Brooke, 2001; Swanson, Mink, & Bocian, 1999), while others suggest a unique comorbid subtype exists. For example, Rucklidge and Tannock (2002) describe poorer rapid naming in adolescents with combined DD and ADHD than those with either ADHD or isolated reading difficulties alone, suggesting a rapid naming deficit is a differentiating factor for a unique combined subtype pf DD and ADHD.

Despite extensive research examining the comorbidity of DD and ADHD, there is emerging evidence that some of the cognitive and behavioural difficulties children with a sole diagnosis of DD experience are characteristic of the difficulties experienced by children with a sole diagnosis of ADHD. For example, children with DD only can experience cognitive difficulties in working memory, sustained attention and other executive functions (which have been described as characteristic of ADHD; Marzocchi et al., 2009; Purvis & Tannock, 2000; Willcutt et al., 2001). Furthermore, difficulties in reading and language, mainly in lexical processing (de Jong et al., 2012; Hale et al., 2005), as well as reduced processing speed have also been described in children with either DD only or ADHD only (Peterson et al., 2017; Shanahan et al., 2006). The presence of behavioural attention difficulties in children with a sole diagnosis of DD raises the idea that ADHD symptoms may co-occur with reading difficulties rather than reflect a distinct profile of difficulties that are present in addition to poor reading in DD, as is typical of comorbidity. This has led to attention-deficit hypotheses regarding potential causes of reading difficulties (Bosse, Tanturier, & Valdois, 2007; Lipowska, Czaplewska, & Wysocka, 2011; Facoetti, et al., 2003), and is consistent with other approaches such as the Multiple Deficit Model which describe neurodevelopmental disorders such as DD and ADHD as the result of both risk and protective factors that may be shared (Pennington, 2006; Willcutt et al., 2010).

An important consideration is that learning to read involves the refinement of linguistic networks, and this reading experience is thought to impact on supplementary sensory and attentional systems working to support reading acquisition (Chokron & Agostini, 1995; Curtis, 1980). Accordingly, behavioural attention difficulties in children with DD may actually reflect less reading experience that has led to reduced opportunity to fine-tune attentional processes to the same degree as typically reading peers who have had more reading exposure. This approach would suggest that ADHD symptoms which co-occur in DD may be secondary to reading dysfunction, rather than contributing to reading difficulties (Huettig, Lachmann, Reis, & Petersson, 2017). Thus, there is increasing recognition of the value of employing a reading matched control group in research studies to shed light on the relationship between reading ability and ADHD symptomology (Goswami, 2015). Using a reading matched control group provides insight that would otherwise be provided by conducting longitudinal follow-ups, which can take several years. Any differences between the DD and reading matched control group help determine whether ADHD symptoms co-occur, specifically by contributing to reading difficulties in DD rather than reflecting suboptimal reading experience.

A complicating factor in the DD literature is the significant heterogeneity in the types of reading difficulties children with DD experience. While the single-deficit phonological theory of DD has been most prominent (Snowling, 2000), phonological difficulties do not explain all cases of DD (Peterson, Pennington, & Olson, 2013). Contemporary reading models posit that reading requires the contribution of two main processing pathways, the *sublexical* (or phonological) and the *lexical* (or surface) routes, which differ in their contribution to reading depending on the word frequency and regularity (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Hence, children with dyslexia may present with reading profiles that vary considerably in terms of the relative sublexical and lexical processes (Castles & Coltheart, 1993; Ziegler et al., 2008); some sit at either ends of the spectrum with marked dissociation of both lexical and sublexical abilities (so-called *lexical* and *sublexical dyslexics* respectively; Castles, Bates, Coltheart, Luciano, & Martin, 2006; Castles, Datta, Gayan, & Olson, 1999), whereas the majority fall between these extremes (known as *mixed* dyslexics; Jackson & Coltheart, 2001).

The nature and severity of ADHD symptoms vary across children with a sole diagnosis of DD (Germanó, Gagliano, & Curatolo, 2010), which makes appropriate diagnosis and treatment particularly challenging. While some children might experience few, if any, ADHD symptoms, other children experience significant symptoms that warrant concern but are not prominent enough to receive a diagnosis, which can preclude them from appropriate treatment (Denckla, 1993). Previous studies have suggested that cognitive attentional difficulties vary across individuals with DD with different reading profiles (Facoetti, Zorzi, Cestnick, Lorusso & Molteni, 2006; Valdois, Bosse, Ans, Carbonnel, & Zorman, 2003). Thus, reading profile may provide a promising approach to identify which children with DD are more likely to experience behavioural attention symptoms, providing valuable information for clinicians to develop tailored management plans for children with DD.

This study aimed to firstly determine the presence of co-occurring ADHD symptoms in a sample of children diagnosed only with DD by comparing them to age matched controls as well as reading matched controls. It was expected that children with DD only would demonstrate higher levels of ADHD symptoms than age matched children, but whether these would be evident when compared to reading matched controls was not clear based on the current literature. A second aim was to examine whether a specific type of reading profile is associated with co-occurring ADHD symptoms in children with DD only. It was expected that children with predominant lexical (rather than sublexical or mixed reading profile) difficulties would experience higher levels of co-occurring ADHD symptoms given lexical difficulties have been observed in both children with DD and ADHD (de Jong et al., 2012).

Method

Participants

This study uses data from a larger project that examined attention in children with DD only using neuropsychological and electrophysiological measures (Stefanac et al., 2019). Participants were 41 children with DD only (20 females) and 41 typically developing children, of whom 24 (13 females) were matched to DD group for chronological age (Age Matched controls; AM) and 17 (9 females) were matched to the DD children for reading age (Reading Matched controls; RM). Participants with DD only were recruited from local paediatric clinics specialising in learning difficulties and community support groups for parents of children with learning and academic challenges, and were required to have a diagnosis of specific learning disorder in reading by a psychologist or neuropsychologist, according to current DSM-5 criteria, but no other formal comorbid diagnoses, including ADHD. Typically developing participants were recruited from local schools and the general community via advertisements, and had no history of a learning difficulty or developmental delay. Children were eligible to participate if they were right-handed, aged 8-16 years, reported normal or corrected to normal vision, normal hearing, no history of developmental delay, intellectual disability (Full Scale IQ < 70), autism spectrum disorder, behavioural or emotional disorders, and had no known neurological history including head injury with loss of consciousness.

Measures

Word reading ability.

The word reading subtest of the Wechsler Individual Achievement Test - Second Edition, Australian and New Zealand Standardised Edition (WIAT-II-A&NZ; Wechsler, 2005) measured word reading ability. Participants read aloud a list of words of increasing difficulty. A point was awarded for each correctly pronounced word, with the test discontinued after seven consecutive errors (scores of 0). A total raw score (range 0 - 131), an age standardised score (M = 100, SD = 15) and reading age equivalent was calculated for each participant.

Reading profile.

The Castles and Coltheart Test 2 (CC2) assessed lexical and sublexical abilities thought to underlie single word reading (Castles & Coltheart, 1993; Castles et al., 2009). It comprises 165 written stimuli, a list of 55 nonwords (e.g., nonsense words such as ‘gop’) that can only be successfully read through the sublexical pathway, a list of 55 irregular words (e.g., 'yacht') that can only be read accurately via the lexical route, and a list of 55 regular words that can be read accurately by either route. The regular and irregular words are matched on frequency, length and grammatical class. The nonwords also vary in their length and in the complexity of the grapheme-phoneme translations. Participants read aloud items one at a time randomly presented from each list and of increasing difficulty. The test was discontinued for a list when 5 consecutive errors were made in that list. Responses were audio-recorded. Two independently trained researchers double-scored the test using the audio-recordings. In cases where there was disagreement, a third researcher determined the final score.

Reading profile was calculated as the ratio of the total number of items accurately read from the nonword and irregular lists divided by the total number of items in each list; (raw $score_{nonword}$ - raw $score_{irregular}$) / 55, with scores ranging from -1 to +1. Negative values reflected poorer nonword readers (i.e., poorer relative sublexical skills), positive values were obtained for those with poorer irregular word readers (i.e. poorer relative lexical skills), and a score of zero reflected equivalent skills across both word types. Larger values indicated greater disparity between sublexical and lexical skills.

ADHD symptoms.

The Conners 3rd Edition (Conners 3) Parent Short-Form (Conners, Pitkanen, & Rzepa, 2008) assessed behavioural ADHD symptoms over the preceding month. The questionnaire yields six symptom sub-scales that measures core ADHD symptoms of inattention and hyperactivity/impulsivity as well as associated problems with learning, executive functioning, aggression and peer relations. Raw scores and standardised *T*-scores based on age- and sex- normative data (*M* = 50, *SD* = 10) were used. As per the manual, *T*-scores ≤ 59 were considered 'average', between 60-64 'high average', 65-69 'elevated' and scores ≥ 70 ' very elevated'.

Intellectual functioning.

The short form of the Wechsler Intelligence Scale for Children - Fourth Edition (WISC-IV-SF; Weschler et al., 2003), was used to measure intellectual ability. Participants completed seven subtests (block design, similarities, vocabulary, matrix reasoning, digit span, coding and symbol search) that were summed to generate an overall intellectual functioning score (Full Scale Intelligence Quotient Score). In addition, four index scores were calculated; Verbal Comprehension, Perceptual Reasoning, Working Memory and Processing Speed. Scores used were age-standardised and generated using Australian sample normative data (*M* = 100, *SD* = 15).

Socioeconomic status.

The Hollingshead Four-Factor Index of Socioeconomic Status (Hollingshead, 1975) is a parent-rated questionnaire designed to estimate the socioeconomic status of a child's family based on four domains: marital status (single, married, divorced), employment status (employed, unemployed), the highest level of education (0 = not applicable or unknown to 7 = graduate/professional training) and occupation (0 = not employed to 9 = higher executive, proprietor of large businesses, major professional). In this study, an index score was computed for each parent by summing their occupation score multiplied by 5, and their education score multiplied by 3, with scores ranging from 8 to 66 (higher scores indicated a higher ranking in social position). Socioeconomic status score for two-parent families was taken as the average and for single-parent families the individual score was taken.

Procedures

Following recruitment and consent, parents completed a brief survey to gather demographic (e.g., date of birth, sex, handedness) and medical history (e.g., details of current diagnoses) information about their child. Following screening, children eligible for the study were then invited to attend an appointment for testing. At this session children completed an individual neuropsychological assessment and participated in an electroencephalogram recording as part of the larger study protocol, while parents completed questionnaires about their child. The study was approved by the University Human Research Ethics Committee (CF 15/3184 – 2015001359) and the Department of Education and Training (2015_002847).

An initial neuropsychological screening was conducted to confirm the absence of intellectual disability, the presence of reading difficulties in children with DD only based on a score on the Word Reading subtest of the Wechsler Individual Achievement Test - Second Edition, Australian and New Zealand Standardised Edition (WIAT-II-A&NZ) at least 1.5 SD below age-appropriate levels, and age appropriate reading in typically developing control children based on a score on the Word Reading subtest within ±1 SD of age-corrected means. Test scores were accessed for two participants with DD only who had undergone neuropsychological assessment within the preceding 12-18 months. Results from neuropsychological screening were used to match control participants to the DD only sample. Independent samples t-tests confirmed the absence of statistical differences on key matching variables of chronological age, $t(63) = 0.37$, $p = .715$, 95% CI [-0.67, 0.96], reading age, $t(56) = -0.64$, $p = .525$, 95% CI [-1.43, 0.74], socioeconomic status score, $t(63) = 1.41$, $p = .164$, 95% CI [-1.92, 11.10] and $t(56) = 1.33$, $p = .188$, 95% CI [-2.53, 12.56], and FSIQ, $t(63) = 0.58$, $p = .562$, 95% CI [-5.09, 9.28] and $t(56) = 0.94$, $p = .349$, 95% CI [-4.08, 11.34].

Statistical Analyses

A series of independent linear regressions were conducted to compare the DD only group and AM controls, and then the DD only group and RM controls on ADHD symptoms measured by the Conners 3 subscales; inattention, hyperactivity/impulsivity, learning problems, executive functioning, aggression and peer relations using raw scores. Analyses were adjusted for child sex given ADHD symptomology is known to vary across males and females (Rucklidge, 2010). Bonferroni corrections were applied for multiple comparisons and adjusted p-values used to determine statistical significance. Then, for any identified co-occurring ADHD symptom in children with DD only, moderation analyses were conducted with the DD only and AM groups to explore whether reading profile (relatively poorer lexical or sublexical difficulties, or a mixed profile) moderated the relationship between word reading ability and the co-occurring ADHD symptom in children with DD only. Where moderation was found, follow-up simple slopes analyses were performed and the Johnson-Neyman technique was used to reveal the true zone of significance, identifying the precise level of the reading profile at which the relationship between word reading ability and the co-occurring ADHD symptom(s) became statistically significant. Analyses were performed in IBM SPSS Statistics Version 25. The PROCESS macro was used to conduct moderation analyses (Hayes, 2013) with the HC3 (Davidson-MacKinnon) heteroscedasticity-consistent inference applied.

Results

Participant Characteristics

Descriptive information was obtained for group comparisons and to match DD participants to controls on age (age matched controls) and word reading age equivalent (reading matched controls; see Table 1 below). Groups were similar on SES and overall IQ but differed, as expected, on processing speed and working memory indices (Jeffries & Everatt, 2004).

Table 1. *Participant Characteristics*

	Developmental Dyslexic (DD) only Group N = 41	Age matched (AM) Control Group N = 24	Reading matched (RM) Control Group N = 17
	M (SD)	***M (SD)***	***M (SD)***
Age (years)	12.05 (1.65)[b]	12.20 (1.48)	9.93 (0.74)
Word reading ability (WIAT-II-A&NZ)			
Word Reading Raw Score	82.24 (15.98)[a]	120.50 (4.58)	87.35 (9.31)
Word Reading Standard Score	69.32 (14.67)[a, b]	108.67 (7.57)	105.29 (9.25)
Word Reading Age Equivalent (years)	8.92 (1.61)[a]	15.49 (2.33)	8.57 (2.42)
Reading profile (CC2)			
Regular Word Reading	29.54 (8.08)[a, b]	48.50 (3.51)	31.71 (7.39)
Nonword Reading	14.39 (7.71)[a, b]	40.75 (6.14)	20.29 (8.44)
Irregular Word Reading	17.95 (4.93)[b]	30.33 (5.00)	13.47 (4.11)
Reading Profile Score	-0.06 (0.10)[a, b]	0.19 (0.12)	0.12 (0.14)
ADHD symptoms (Conners 3)			
Inattention Raw Score	6.76 (3.72)[a, b]	3.13 (3.11)	4.00 (2.74)
Inattention *T*-Score	65.68 (14.18)[a, b]	51.87 (10.99)	54.35 (9.53)
Hyperactivity Raw Score	6.24 (4.62)[a]	3.08 (2.39)	4.71 (2.47)
Hyperactivity *T*-Score	65.29 (14.35)[a]	55.46 (9.78)	58.29 (9.16)
Learning Problems Raw Score	8.80 (3.70)[a, b]	2.33 (2.97)	2.88 (2.57)
Learning Problems *T*-Score	74.17 (13.53)[a, b]	50.54 (10.65)	52.29 (10.24)
Executive Functioning Raw Score	7.10 (3.92)[a, b]	3.46 (2.93)	4.53 (2.55)
Executive Functioning *T*-Score	63.54 (15.44)[a, b]	50.17 (9.10)	55.47 (8.32)
Aggression Raw Score	1.83 (2.10)[a]	0.50 (0.72)	1.65 (2.91)
Aggression *T*-Score	57.41 (13.58)[a]	48.21 (4.61)	54.88 (14.62)
Peer Relations Raw Score	3.78 (2.46)	2.67 (1.76)	3.00 (1.87)
Peer Relations *T*-Score	69.93 (12.22)	63.50 (11.06)	66.76 (12.03)

Hollingshead Socioeconomic Status Score	47.80 (2.18)	52.40 (10.08)	52.82 (10.46)
Intellectual functioning (WISC-IV-SF)			
Full Scale IQ	100.78 (14.39)	102.88 (13.27)	104.41 (10.25)
Perceptual Reasoning Index	102.85 (17.00)	101.46 (14.65)	106.65 (14.39)
Processing Speed Index	95.56 (12.02)[b]	93.17 (13.20)	105.59 (12.24)
Working Memory Index	97.20 (10.69)[a]	112.71 (14.14)	101.18 (15.16)
Verbal Comprehension Index	106.83 (15.57)	103.33 (12.25)	107.94 (9.16)

[a] group difference between DD group and AM controls

[b] group difference between DD group and RM controls

Determining Co-occurring ADHD Symptoms in Children with DD: Comparisons with AM and RM Controls

The DD only group demonstrated higher levels of both inattention and hyperactive/impulsive ADHD symptoms than AM controls, with greater difficulties also reported in executive functioning, aggression and learning problems, but not peer relations. Compared with RM controls, the DD only group demonstrated higher levels of inattention ADHD symptoms as well as executive functioning and learning problems, with no differences in hyperactive/impulsive ADHD symptoms nor aggression (see Table 2 for a summary).

able 2. *Comparisons between DD and both AM and RM groups on the Conners 3 ADHD Rating Scale Symptom Ra*

	Developmental Dyslexic (DD) only Group vs Age Matched (AM) Control Group				**Developmental I Matc**	
	b	**[95% CI]**	***p***	η^2	***b***	**[95**
Inattention	1.80	[0.89, 2.70]	< .001*	0.21	2.77	[0.7
Hyperactivity/Impulsivity	1.55	[0.53, 2.57]	.003*	0.15	1.50	[-0.8
Learning Problems	3.25	[2.36, 4.14]	< .001*	0.46	5.95	[3.9
Executive Function	1.83	[0.89, 2.76]	< .001*	0.20	2.59	[0.5
Aggression	0.66	[0.21, 1.11]	.004*	0.13	0.16	[-1.2
Peer Relations	0.54	[-0.03, 1.10]	.065	0.09	0.77	[-0.3

Vote. *b* = unstandardised regression coefficient. CI = confidence interval. η^2 = eta-squared. * = statistical significance

Examining the Role of Reading Profile in the Association between Reading Ability and Co-occurring ADHD Symptoms

Moderation analyses revealed that reading profile was a significant moderator of the association between reading ability and both inattention ADHD symptoms and executive function problems, despite neither word reading ability nor reading profile having a direct effect independently (see Table 3 for a summary).

For the association between reading ability and inattention ADHD symptoms, the zone of significance (based on the Johnson-Neyman technique) was a reading profile score ≥ 0.0239 (i.e., 1 or more nonwords read correctly than irregular words), and for the association between reading ability and executive function problems the zone of significance was a reading profile sore ≥ 0.2082 (i.e., 11 or more nonwords read correctly than irregular words). Thus, only children with poorer reading ability (i.e., those in the DD group) had 'very elevated' levels of inattention symptoms and executive functioning problems if they also had poorer relative lexical reading skills. For readers with poorer relative sublexical reading skills on the other hand, the relationship between word reading ability and inattention symptoms or executive functioning problems was not significant. Hence, both children with poor reading and age-appropriate readers had similar inattention ADHD symptoms and executive functioning scores (see Figure 1).

Table 3. *The Relationship Between Word Reading Ability (WIAT-II-A&NZ) and Inattention and Executive Functioni*
Moderated by Reading Profile (CC2) in Children with Developmental Dyslexia and Age Matched Controls.

Model		***b* [95% CI]**	***SE***
1	Constant	81.03	10.
Inattention		[60.95, 101.11]	
$F(3,61) = 9.54$, $p < .001$, $R^2 = 0.24$	Word Reading Ability	-0.20	0.1
		[-0.42, 0.03]	
	Reading Profile	116.68	66.
		[-16.20, 249.55]	
	Word Reading Ability x Reading Profile	-1.40	0.6
		[-2.71, -0.08]	
2	Constant	72.04	10.
Executive Function		[51.70, 92.39]	
$F(3,61) = 8.13$, $p < .001$, $R^2 = 0.19$	Word Reading Ability	-0.11	0.1
		[-0.34, 0.11]	
	Reading Profile	101.44	67.
		[-33.02, 235.89]	
	Word Reading Ability x Reading Profile	-1.30	0.6
		[-2.60, -0.01]	

Note. *b* = unstandardised regression coefficient. *SE* = standard error. *B* = standardised regression coefficient. R^2 = R-

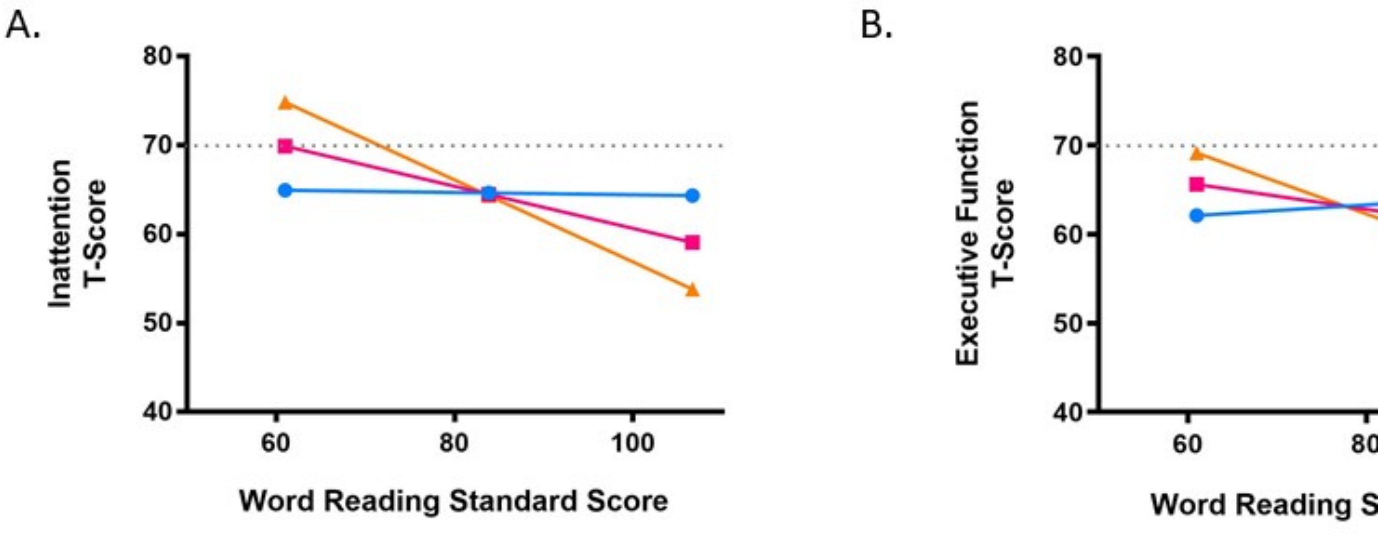

Figure 1. Relationship between word reading ability (Word Reading Standard Score on the WIAT-II-A&
functioning (B) symptoms (Conners 3 Age-Standardised Scale Score) for the DD only group and AM contr
(CC2 score). For graphic visualisation of the relationship, three profile scores along the continuum of reading
from the mean of predictor variable as per Hayes (2013). This corresponded to -0.13 (poorer lexical readers) an
indicating a discrepancy of 7 and 10 words respectively, as well as at 0; indicating equivalent accuracy across
A Conners subscale *T*-score ≥ 70 (grey dotted line) indicates 'very elevated' level of symptoms and of clinica

Note. * = $p < .05$.

Discussion

Although there is an established literature regarding the comorbidity of DD and ADHD (Willcutt & Pennington, 2000), little is known about whether the behavioural attentional symptoms commonly associated with ADHD are experienced by children with a sole diagnosis of DD thereby co-occur with reading difficulties. There is also debate as to whether attentional difficulties in children with DD occur over and above poor reading ability, or if they arise secondary to suboptimal reading exposure. We found that children with DD only experienced a range of ADHD symptoms compared with typically developing, same-age peers, including greater inattention and hyperactive/impulsive ADHD symptoms, executive dysfunction, aggression and learning problems, which are evident despite these children not having a comorbid diagnosis of ADHD or being flagged as having attentional problems. Importantly, compared with reading matched controls, children with DD specifically displayed more inattention symptoms and executive function problems, suggesting that inattentive ADHD symptoms and executive difficulties are not associated with reduced reading exposure or immature reading networks.

Overlap between DD and ADHD symptoms has been previously noted in the literature (Marzocchi et al., 2009; Purvis & Tannock, 2000; Willcutt et al., 2001), suggesting common underlying risk factors consistent with a Multiple Deficit Model of DD (Pennington, 2006). The results of our study provide specific evidence that behavioural inattention and executive function problems are present in children with a sole diagnosis of DD, even after accounting for reading ability, suggesting they co-occur alongside reading difficulties and may form part of the DD profile, representing markers of shared risk for both ADHD and DD. We speculate that externalising behaviours such as hyperactivity and aggression, may instead reflect consequences of reading problems that become evident at later stages of development for children with DD only, after they fail to progress in their reading in the same way their typically developing peers do. Although longitudinal studies are needed to confirm this hypothesis, this suggestion is in keeping with the phenomenon of a widening gap in abilities and the emergence of more problematic behaviours with increasing age, which is commonly observed in developmental disorders (Anderson, Northam, & Wrennal, 2018). It may also explain why symptoms of inattention and executive function problems are more commonly reported in younger samples of children with DD compared with other ADHD symptoms, such as hyperactivity (Marzocchi et al., 2009; Purvis & Tannock, 2000; Rucklidge & Tannock, 2002; Willcutt et al., 2001).

This study also examined whether children with a sole diagnosis of DD who are more likely to experience co-occurring ADHD symptoms can be identified using their reading profile. We found that children with DD only experienced higher levels of inattention symptoms and executive functioning problems than same-age peers, however this was particularly pronounced for children with relatively poorer lexical reading abilities. This subgroup of children with DD specifically displayed co-occurring ADHD symptoms in the 'elevated' (executive function) or 'very elevated' (inattention) range. In contrast, children with DD and relatively poorer sublexical reading abilities, or a mixed profile, had similar levels of ADHD symptoms as typically developing peers, with inattention and executive functioning problems largely in the 'average' and 'high average' range. Interestingly, lexical reading difficulties have been observed in samples of children with DD only (de Jong et al., 2012) or ADHD only (Hale et al., 2005), suggesting that lexical reading may be more impacted by lapses in attention than sublexical reading which is in line with cognitive models purporting that successful execution of the lexical route requires considerable top-down executive control and controlled attentional processing (Paap & Noel, 1991).

Interestingly, although our DD only sample as a group were more likely to experience co-occurring ADHD symptoms than same-age peers, neither their standardised word reading ability nor type of reading difficulties were predictive of co-occurring ADHD symptoms alone. While it might be intuitive to assume that children with more severe reading difficulties would also be more vulnerable to behavioural attention difficulties, the results of this study tells us is that it is not necessarily the severity of the reading difficulties that determines which individuals with DD are more likely to experience ADHD symptoms. Rather, our findings point to the combination of both reading ability and reading profile as being crucial for identifying children with DD who are likely to experience co-occurring ADHD symptoms.

Together, the results of this study raise the concern that behavioural attention difficulties are likely going unnoticed in a large proportion of children with a sole diagnosis of DD, which could be impacting on functioning. Results further illustrate a more nuanced relationship between attention and reading whereby specific ADHD symptoms (i.e., inattention and executive dysfunction) co-occur with reading difficulties in DD even in pure cases of the disorder, over and above reduced reading ability, while other ADHD symptoms (i.e., hyperactivity/impulsivity and aggression) are only evident compared to typically reading peers who have had greater exposure to text. From a theoretical perspective, this demonstrates that specific indices of behavioural attention dysfunction may be evident alongside reading difficulties and therefore inherent to DD. The results also showed that reading profile can be used to identify the children with DD only more likely to experience behavioural attention difficulties; specifically, children with relatively poorer lexical abilities. Thus, we present evidence to suggest that clinicians working with children who have a diagnosis of DD should seek to characterise both the nature and severity of a child's reading difficulties, rather than looking solely at overall reading ability to forecast outcomes. Common treatment approaches for children with DD include direct reading instruction and tailored teaching (Kelly & Phillips, 2016), while pharmacological treatments are often the preferred approach for ADHD (Millichap, 2009). Therefore, being able to identify the children with DD who experience symptoms of ADHD in this way can help earmark who may benefit from the use of strategies to support attention in the classroom and to supplement reading interventions in DD cohorts.

While the findings and implications of this study are novel and clinically relevant, they require replication in larger samples to provide greater power to detect potentially subtle but important differences between subgroups of children with DD. Although the groups used in the study may be considered relatively small, the reduced sample is considerable given the studies' experimental nature and the strict recruitment and screening criteria necessary to ensure the DD sample did not present with diagnosed comorbidities. Our reading matched control group was only matched on one key measure of reading ability, which meant we were not able to consider a range of reading skills, including reading speed, fluency and spelling ability. Although matching participants on a combination of reading skills would be ideal, we acknowledge that this makes recruitment of large samples even more difficult. Nonetheless, we encourage researchers to endeavour to control for reading ability and reading experience in the future by using similar methodologies. It may also be useful to consider how other cognitive skills such as working memory and processing speed may mediate the relationship between ADHD symptoms and reading ability. Comparisons to younger, reading matched control participants provides important insight into the relationship between reading ability and the development of skills that supplement reading such as attention that are otherwise not captured with traditional age matched designs. However, it is important to note that the nature of this relationship is complex and unlikely to be unidirectional. While various control groups can be used as analogues of development, we can only speculate as to how those with DD deviate from their typically developing counterparts using these comparisons. Longitudinal studies that track the development of reading acquisition and attention over time would help clarify the nature of this relationship. Understanding the reading-attention relationship in this way is particularly pertinent as the nature and severity of symptoms of both disorders is also known to manifest differently over time (Boada, Willcutt, & Pennington, 2012). Furthermore, this study examined behavioural symptoms of ADHD using the Conners 3 parent form. Although this tool is particularly useful for clinical translation as it is commonly used to diagnose ADHD (Gallant et al., 2007; Gallant, 2008), informant-report measures have inherent limitations as scores can reflect factors that may not be the direct result of attentional problems such as a reporters own interpretations of behaviour as well as their past experiences, or lack thereof, of typical versus atypical child development. In addition, there is increasing awareness that symptoms of ADHD do not manifest solely in a child's behaviour. For instance, there is a substantial literature documenting cognitive difficulties in ADHD samples (Castellanos, Sounga-Barke, Milham, & Tannock, 2006). Thus, skills measured in this study such as executive functioning may not be adequately measured behaviourally, so replication of these findings with a range of measures including experimental and cognitive measures would be of interest.

In conclusion, this study presents novel evidence that ADHD symptoms are evident in children with a sole diagnosis of DD and that specific symptoms of inattention and executive dysfunction co-occur in DD, emphasising the need for further investigation into the shared underlying risk between DD and symptoms of ADHD. Crucially, this study revealed that both the type and severity of reading difficulties can help identify which children with DD are likely to experience co-occurring ADHD symptoms. Thus, we suggest reading profile could be used clinically to identify children with DD who may benefit from treatments to reduce inattention and executive-level behavioural difficulties in addition to reading intervention.

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CHAPTER SIX: VISUAL PROCESSING SPEED AS A MARKER OF IMMATURITY IN LEXICAL BUT NOT SUBLEXICAL DEVELOPMENTAL DYSLEXIA

Preamble

One of the most consistent visual attention difficulties reported in the DD literature is a reduced visual attention span. Visual attention span is defined as the number of individual elements that can be correctly recalled after simultaneous presentation of visual stimuli within a given, often very brief, time window (Lobier, Zoubrinetzky, & Valdois, 2012). Knowledge regarding the mechanism that underlies poor visual attention span abilities, as well as the generalisability of these deficits on measures with linguistic and non-linguistic stimuli however, remains elusive (Collis, Kohnen, & Kinoshita, 2012; Lobier et al., 2014). There is little consensus as to whether poor visual attention span deficits represent a defining characteristic of DD, independent of reading ability, or whether it reflects immaturity of reading-attention networks thereby arising as a result of reduced reading exposure (Goswami, 2015).

This study examined visual attention span using a contemporary version of the Theory of Visual Attention (TVA) paradigm (Bundesen, 1990), providing the opportunity to examine underlying components of visual attention span on an individual basis using mathematical computational modelling. In addition to the traditional letter stimuli condition of TVA (i.e., linguistic), a novel version was developed using non-nameable symbols matched to letters on visual complexity (i.e., non-linguistic). Thus, this paper builds on previous studies and is the first to investigate whether visual attention span deficits are consistent across both linguistic and non-linguistic stimuli in DD. This paper also aimed to examine whether visual attention span deficits are seen in children with DD compared to both age matched and reading matched control groups to ascertain whether deficits were evident even after controlling for reading ability. Reading profile was considered to determine whether visual attention span deficits were more prominent in children with DD who presented with a specific reading profile.

This is the first study to show that poor processing speed underpins visual attention span deficits in DD which indexes reading immaturity and is specifically evident in children with relatively poorer lexical reading abilities. This speed deficit was shown to be stimulus-specific, applying only to linguistic information. As a result, the findings provide important insight into the dynamic nature of the relationship between reading acquisition and subsequent visual attention span abilities, while emphasising the importance of understanding individual differences in reading profile when searching for causal factors of DD

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Research Report

Visual processing speed as a marker of immaturity in lexical but not sublexical dyslexia

Nicole Stefanac [a,*], *Megan Spencer-Smith* [a], *Meádhbh Brosnan* [a], *Signe Vangkilde* [c], *Anne Castles* [b] *and Mark Bellgrove* [a]

[a] *School of Psychological Sciences and Turner Institute for Brain and Mental Health, Monash University, Melbourne, Victoria, Australia*
[b] *Department of Cognitive Science, Macquarie University, Australia*
[c] *Department of Psychology, University of Copenhagen, Øster Farimagsgade 2A, 1353 København K, Denmark*

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a b s t r a c t

A visual attention span (VAS) deficit has been widely reported in the Developmental Dyslexia (DD) literature, however, consensus regarding what underlies this problem and the nature of its relationship with reading ability remains elusive. Thirty-two children with DD (15 females) were compared with 23 age matched (12 females) and 17 reading matched controls (9 females) on the combined Theory of Visual Attention (CombiTVA) paradigm with traditional letter and novel symbol conditions. The DD group performed more slowly than the age matched controls in terms of processing speed, but similarly to reading matched controls. Moderation analyses revealed that the difference between the DD group and age matched controls was driven by children with equivalent, or relatively poorer, lexical compared with sublexical reading profiles. Results suggest that reduced processing speed indexes reading immaturity, particularly in DD individuals with relative lexical reading deficits, rather than being a unique contributor to reading dysfunction.

* *Corresponding author*. School of Psychological Sciences and Turner Institute for Brain and Mental Health, 18 Innovation Walk, Monash University, 3800, Vic, Australia.
E-mail address: nicole.stefanac@monash.edu (N. Stefanac). https://doi.org/10.1016/j.cortex.2019.08.004
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1. Introduction

Developmental dyslexia (DD) is a multi-deficit disorder characterised by difficulties with accurate or fluent word reading as well as dysfunction in the cognitive processes that support reading such as visual attention (Lyon, Shaywitz, & Shaywitz, 2003). Visual attention deficits have been argued to predate the onset of phonological problems in DD and be predictive of later reading acquisition (Carroll, Solity, & Shapiro, 2016;

Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012; Franceschini & Bertoni et al., 2017). Nevertheless, establishing whether visual attention deficits are unique to DD, over and above reading ability, has proven difficult.

Despite the ease with which reading occurs for typically developing individuals, the processes underlying successful reading are complex. According to the prominent Dual Route Model (DRM; Coltheart, Curtis, Atkins, & Haller, 1993), reading aloud requires the contribution of two processing pathways; the sublexical and lexical routes. The sublexical route involves deciphering words by parsing them into their smallest written units and serially sounding them out to blend them into a cohesive word. The lexical route involves parallel processing of words as wholes and retrieving corresponding verbal output based on previously learned information. Although the DRM is often conceptualised as comprising two distinct pathways, reading requires activation of both routes concurrently, with their relative contribution varying as a function of word characteristics such as familiarity, length and regularity (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Paap & Noel, 1991; Seidenberg, Waters, Sanders, & Langer, 1984).

The degree to which individuals with DD have problems with lexical and sublexical pathways varies considerably (Ziegler et al., 2008). At one end of the continuum, there are some with relatively poorer lexical reading, so-called *surface* or arguably more appropriately termed *lexical dyslexics*. At the other end are those with relatively worse sublexical skills, so-called *phonological* or *sublexical dyslexics* (Castles, Bates, & Coltheart, 2006; Castles, Datta, Gayan, & Olson, 1999; Jackson & Coltheart, 2001; Peterson, Pennington, & Olson, 2013). Between these extremes, falls the majority of individuals with less marked dissociation of lexical and sublexical skills, known as *mixed dyslexics* (Jackson & Coltheart, 2001). Although some studies have examined heterogeneity in dyslexic samples by statistically defining sub-groups (Zoubrinetzky, Bielle, & Valdois, 2014), determining optimal cut-off criteria has proven problematic (McArthur et al., 2013). In addition, sub- grouping fails to capture variation across the entire spectrum of reading skills. As a result, research capturing the heterogeneity of DD samples by looking at relative lexical and sublexical skills across a continuum is necessary.

Successful reading also requires efficient attentional functions. The Multi-Trace Memory (MTM) model, conceptualises the existence of two procedures involved in reading, a global and an analytic one, in which efficient modulation of attentional control is fundamental (Ans, Carbonnel, & Valdois, 1998; Valdois, et al., 2003). The global and analytic processes differ in the size of the visual attentional window required to extract information from text successfully. In the global mode, the window extends over the entire letter string. In contrast, attention is restricted to the first part of the ortho- graphic sequence (typically a syllable) which then moves sequentially until the entire word has been processed in the analytic mode. At each step, phonological information is accessed and held within a phonological buffer so that the entire sequence is available at the end of processing. The MTM model therefore proposes that, differences in the severity of the VAS deficit will differentially impact on how entire letter strings are inputted via global processes and the sequential processing of letter strings during analytical processing (Bosse & Valdois, 2009). Linking this with the DRM of reading, it is possible that inefficient control of the visual attentional window contributes to the differing reading profiles described in DD samples by the DRM. For instance, an inability to extend the attentional window over the whole sequence of a word could prevent reading in the global mode and would thus bear greater impact on lexical reading, particularly in opaque orthographies such as English with a greater proportion of irregular words requiring simultaneous processing of the entire word letter-string for successful production (Bosse, Tainturier, & Valdois, 2007; Franceschini & Trevisan et al., 2017; Valdois, Bosse, & Tainturier, 2004). On the other hand, deficits in analytical processing of long, multi-letter graphemes common in English can affect phonological decoding via the sublexical route (Zoubrinetzky et al., 2014). They may also arise due to inefficient engagement and disengagement of the attentional window across a word sequence caused by sluggish attentional shifting disturbs access to phonological information, thereby potentially resulting in problems which recruit sublexical reading strategies (Facoetti, et al., 2006; Franceshini et al., 2012).

A number of studies have documented reduced visual attention span (VAS) in individuals with DD compared to their typically developing peers (Bosse et al., 2007). However, the use of linguistic stimuli and verbal report raises criticism that poor performances may reflect deficits in phonological retrieval, rapid-naming, or even in the phonological loop of working memory (Collis, Kohnen, & Kinoshita, 2013; Hawelka & Wimmer, 2008; Ziegler, Pech-Georgel, Dufau, & Grainger, 2010). In response, researchers have utilised non-linguistic stimuli (e.g., symbols) or numerical codes (e.g., digits) in VAS paradigms. Although some report comparable deficits using letters, supporting a global VAS deficit in DD (Jones, Branigan, & Kelly, 2008; Lobier, Peyrin, Pichat, Le Bas, & Valdois, 2014; Lobier, Zoubrinetzky, & Valdois, 2012; Pammer, Lavis, Hansen, & Cornelissen, 2004; Valdois, Lassus-Sangosse, & Lobier, 2012), others have failed to show the same pattern, casting doubt on the generalisability of the VAS theory to all types of stimuli (Collis et al., 2013; Hawelka & Wimmer, 2008; Shovman & Ahissar, 2006; Yeari, Isser, & Schiff, 2017; Ziegler, et al., 2010).

VAS can be linked to distinct attentional and cognitive mechanisms, including processing speed and visual short- term memory (VSTM) capacity (Lobier, Dubois, & Valdois, 2013; Stenneken, Egetemeir, Schulte-Koerne, Mueller, Schneider & Finke, 2011) and reduced VAS in DD has been argued to be accounted for by asymmetrical allocation of attention across space (Vidyasagar & Pammer, 2010). There is also the suggestion that existing letter-name knowledge can influence VAS (Frey & Bosse, 2018) with poor top-down control possibly contributing to inefficient extraction of visual material in individuals with DD who are especially prone to interference and crowding (Roach & Hogben, 2007). Thus, reduced VAS may have multiple underlying contributing processes. To address this limitation, studies have utilised parameter-based measures of visual attention, the most prominent being the Theory of Visual Attention (TVA; Bundesen, 1990). With strong links to the biased-competition view of visual attention pioneered by Desimone and Duncan (1995) and combining both temporal and spatial aspects of attention, the TVA framework assumes visual items are processed in parallel, competing for selection into a limited VSTM store. Selection is biased according to an individual's early sensory detection thresholds (perceptual threshold), speed of information processing (processing speed), the capacity of their VSTM store (VSTM capacity), their ability to inhibit distractors (top-down control), and the distribution of attentional resources across space (attentional weighting), with the outcome being the number of items accurately reported.

The TVA framework is valued for understanding visual attention in a range of clinical samples (Habekost, 2015) and has been utilised previously in both child and adult DD cohorts. In general, processing speed is the most reliable impairment found in both samples (Bogon, Finke, & Stenneken, 2014; Dubois et al., 2010; Stenneken et al., 2011; see Bogon, Finke, & Stenneken, 2014 and Habekost, 2015 for a review). VSTM capacity was shown to be comparable in adults with DD and their same-age peers (Stenneken et al., 2011). However, a marked reduction in VSTM capacity has been revealed in some, but not all, participants in younger cohorts (Bogon, Finke, & Schulte-Korne et al., 2014; Dubois et al., 2010). Similarly, inconsistent results have been reported for the estimation of spatial weighting. Adults with DD have not shown the typical advantage for processing stimuli in the left, compared with the right, hemifield, but instead demonstrated a symmetrical distribution of attentional weights across the hemifields (Stenneken et al., 2011). In children, symmetrical spatial weighting has been observed in both typical readers and those with DD, suggesting that the leftward bias may emerge during later typical development with increased expertise in reading (see also Hausmann, Waldie, & Corballis, 2003; Sireteanu, Goertz, Bachert, & Wandert, 2005). Finally, none of these studies report differences in top-down control for either children or adults with DD (Bogon, Finke, & Schulte- Korne et al., 2014; Dubois et al., 2010; Stenneken et al., 2011). Even with the growing evidence for attentional dysfunction in DD, mixed findings cast doubt on the unique role of VAS deficits in the development of DD. An alternative hypothesis is that attentional deficits arise as a consequence of the failure to effectively train these skills due to reduced reading ability and practice in DD samples. As Goswami (2015) argues, attentional and sensory theories of DD are debated as there is limited evidence that any one single deficit precedes reading difficulties and is consistently present in all cases of DD (Perry, Zorzi, & Ziegler, 2019). They are also challenged by research showing that reading acquisition influences the development of these skills with habits such as reading direction resulting in differences in a variety of attentional abilities (Chokron & Imbert, 1993). Accordingly, there is debate regarding the directionality of the relationship between VAS and poor reading. Thus, traditional age matched control comparisons must now be supplemented by reading matched control designs, where those with DD are compared with younger, typical readers of equivalent reading ability. Using this methodology, children with DD who do not demonstrate a significant phonological deficit have been shown to have poorer VAS than reading matched controls (Zoubrinetzky et al., 2014) and adopting similar designs have also been shown to have poorer VAS than those whose DD is characterised by phonological difficulties despite being matched on reading ability (Bosse et al., 2007). However, it is noted that these results are still under debate in the literature (see Lobier & Valdois, 2015 for a review). Inconsistency in previous studies may also arise from heterogeneity of reading profiles. If the attentional requirements of the lexical and sublexical reading routes differ, and those with DD present with varying difficulties in their lexical and sublexical skills, then VAS dysfunction may only be evident in those presenting with a specific reading profile (relative lexical or sublexical reading deficits). As such, past positive reports of a VAS deficit could reflect the predominant ascertainment of DD participants biased towards a particular type of reader.

Here we leveraged the TVA to determine the cognitive processes contributing to VAS deficits in DD. Our study had three primary aims; (1) to identify deficits that were unique to DD by comparing these individuals to both reading matched and age matched controls; (2) to test if deficits represented a global impairment, generalising across linguistic (letters) and non-linguistic (symbols) stimuli; and (3) examine if a continuous measure of reading profile could dissect the heterogeneity of DD by moderating the relationship between TVA attentional measures and reading ability.

We hypothesised that children with DD would evince poorer processing speed but equivalent top-down control, attentional weighting, and VSTM capacity, when compared with age matched controls. If VAS deficits uniquely contribute to DD, then differences were also expected relative to reading matched controls. If VAS deficits arise independently of access to phonology, then domain general deficits (irrespective of letter or symbol stimuli) were also anticipated. Given that the size of the attentional window is expected to primarily constrain global processing, we hypothesised that reading profile would moderate the relationship between TVA components and word reading ability such that those with dominant lexical difficulties would present with VAS deficits and therefore drive any group differences.

1. Materials and method

1.1. *Procedure*

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/ exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study. An initial pool of 217 participants with DD were recruited from local paediatric clinics specialising in the assessment of learning difficulties, as well as community support groups for parents of children with academic challenges. 81 control participants were recruited from local schools and the community via advertisements. Interested participants were deemed eligible if they were right-handed, aged between 8 and 16 years, reported normal or corrected to normal vision, normal hearing, no history of developmental delay, attention-deficit hyperactivity disorder (ADHD), intellectual disability, autism spectrum disorder, behavioural or emotional disorders, and no known neurological history including head injury with loss of consciousness. The DD sample was required to have a diagnosis of specific learning disorder (SLD) in reading by a psychologist or neuropsychologist, according to current DSM- 5 criteria, but no other comorbid diagnoses. Control participants had no history of any learning difficulties or delays.

Neuropsychological screening was conducted to confirm the absence of intellectual disability (Full-scale IQ < 70) and parent-reported symptoms of ADHD (scores within the 'very elevated' range for either the inattention or hyperactivity/ impulsivity sub-scales of the Conners Third Edition). The presence of reading difficulties in the DD sample was confirmed (score at least 1.5 SDs below age-appropriate levels on word reading subtest of the WIAT-II-A&NZ). Control participants performed within ±1 SD of age-corrected means for word reading, indicative of age-appropriate reading ability. Test scores were accessed for two participants in the DD sample who had undergone neuropsychological assessment within the preceding 12-18 months.

Neuropsychological results were also used to match control participants to the DD sample on the basis of either chronological age (age matched; AM controls) or reading age (reading matched; RM controls). Independent samples t-tests confirmed the absence of statistical differences on key matching variables of chronological age, $t = 1.92$, $p = .060$, 95% CI [-.02, .97], reading age, $t = 1.39$, $p = .170$, 95% CI [-.14, .75], and socioeconomic status, $t = 5.58$, $p = .131$, 95% CI [1.26, -9.45] and $t = -.81$, $p = .423$, 95% CI [-6.00, 2.56]. Equivalence testing confirmed groups were classed in at least the average range and met criteria for clinical equivalence on overall measures of intellect and ADHD symptomology (Inattention and Hyperactivity/ Impulsivity) using reliable change indices according to Cribbie and Arpin-Cribbie (2009) and Mara and Cribbie (2012; see Appendices A to C). Following screening, eligible participants attended a testing session to complete the experimental protocol (see Fig. 1 for flow of participants through this protocol). The study was approved by the University Human Research Ethics Committee (CF15/3184_2015001359) and the Department of Education and Training (2015_002847). In accordance with the Helsinki declaration, informed consent was provided by all parents and verbal assent was confirmed by all participating children. No part of the study procedures was pre-registered prior to the research being conducted.

1.1. *Participants*

The final sample included 72 participants across the three groups; 32 with DD (15 females), 23 in the AM control group (12 females) and 17 in the RM control group (9 females; see Table 1 for participant characteristics).

1.2. *Materials*

1.2.1. *Word reading ability*

The word reading subtest of the Wechsler Individual Achievement Test - Second Edition, Australian and New Zealand Standardised Edition (WIAT-II-A&NZ; Wechsler, 2005) measured word reading ability. This subtest is reported to have excellent test-retest reliability, r = .96, (Wechsler, 2005). Participants read aloud a list of words of increasing difficulty. A point was awarded for each correctly pronounced word, with the test discontinued after 7 consecutive errors (scores of 0). A total raw score (range 0-131) as well as an age-standardised score (M = 100, SD = 15) were calculated for each participant.

1.2.2. Intellectual functioning

The short form of the Wechsler Intelligence Scale for Children- Fourth Edition (WISC-IV-SF; Wechsler, 2003) was used to measure intellectual ability according the methods outlined by Crawford, Anderson, Rankin, and MacDonald (2010). Participants completed seven subtests (block design, similarities, vocabulary, matrix reasoning, digit span, coding and symbol search), summed to generate an age-standardised full-scale intelligence quotient (FSIQ) and four index scores; verbal comprehension, perceptual reasoning, working memory and processing speed (M = 100, SD = 15). According to Crawford et al., (2010) the WISC-IV-SF has been reported to have excellent reliability for overall FSIQ, r = .97 (similar to the full- length version at r = .96).

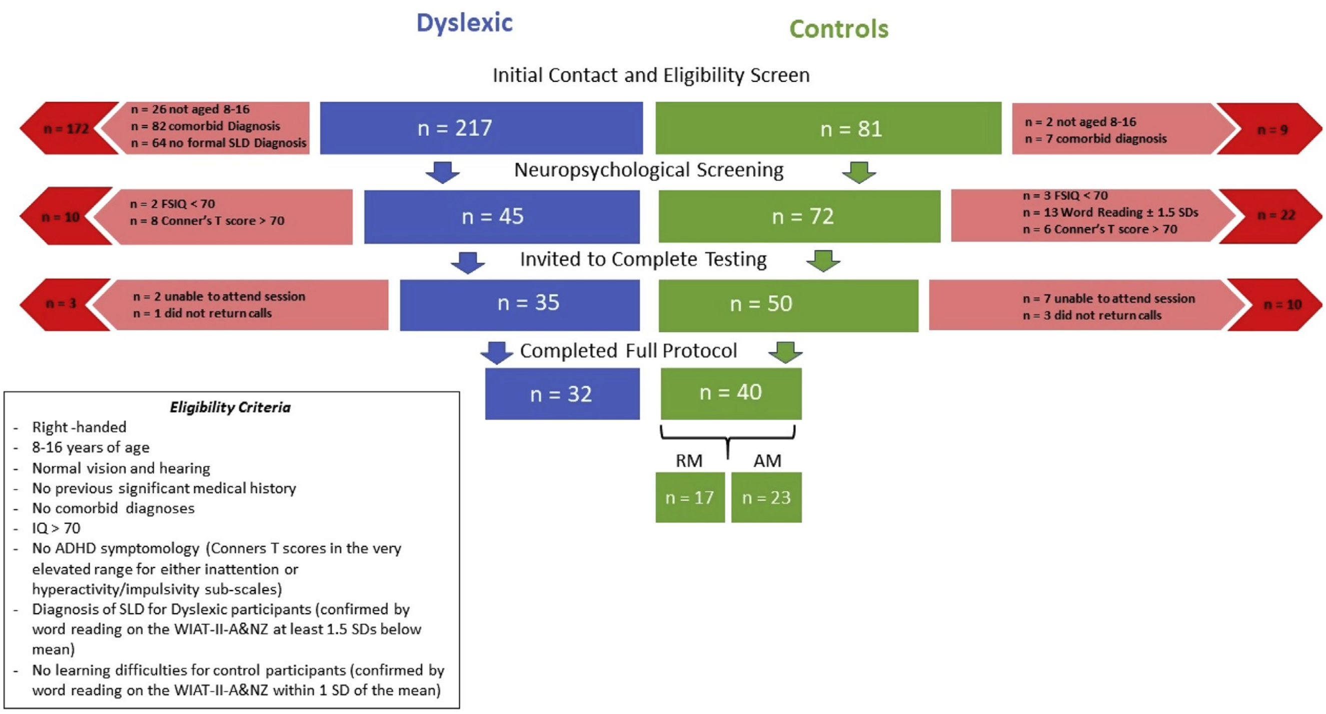

Fig. 1. Flow of participant recruitment through protocol.

Table 1. Participant characteristics

	Developmental Dyslexic Group	Age matched Controls	Reading matched Controls
	M (SD)	*M (SD)*	*M (SD)*
Age (years)	12.28 (.88)[b]	12.76 (.95)	8.90 (.71)
Hollingshead Socioeconomic Status Score	50.95 (17.62)	55.58 (13.80)	56.62 (14.08)
Intellectual Functioning (WISC-IV-SF)			
FSIQ	99.84 (5.71)	105.7 (6.24)	105.88 (6.36)
PRI	98.81 (15.70)	101.70 (14.93)	106.65 (14.39)
PSI	92.91 (11.52)[a]	112.56 (13.16)	105.59 (12.24)
WMI	92.22 (8.30)[a]	112.39 (14.37)	101.18 (15.16)
VCI	102.59 (13.51)[b]	103.78 (12.32)	112.94 (9.16)
Word Reading Ability (WIAT-II-A&NZ)			
Word Reading Raw Score	88.22 (8.73)[a]	120.48 (4.46)	93.47 (8.88)
Word Reading Standard Score	70.78 (7.05)[a,b]	109.30 (7.44)	99.35 (7.65)
Word Reading Age Equivalent	8.19 (2.74)[a]	15.53 (2.35)	8.49 (2.72)
ADHD Symptoms (Conners-3 – Parent Report)			
Inattention	54.75 (10.33)	50.65 (8.92)	54.12 (9.08)
Hyperactivity/Impulsivity	59.25 (6.64)	54.35 (7.20)	57.53 (7.89)
Learning Problems	76.84 (10.03)[a,b]	50.35 (10.78)	51.35 (7.38)
Executive Functioning	63.75 (15.24)[a,b]	49.96 (9.25)	55.41 (8.22)
Defiance/Aggression	57.16 (12.27)[a,b]	48.35 (4.66)	52.47 (9.60)
Peer Relations	70.63 (12.27)[a,b]	63.70 (11.26)	63.06 (6.91)
Reading Profile (CC2)			
Regular Word Reading	29.16 (7.65)[a,b]	48.87 (3.08)	31.71 (7.16)
Nonword Reading	14.00 (6.97)[a,b]	40.52 (5.20)	20.29 (8.19)
Irregular Word Reading	17.94 (4.75)[a,b]	31.83 (6.14)	13.47 (3.98)
Reading Profile	−.07 (.09)	.16 (.17)	.12 (.14)

Note. WISC-IV-SF = Wechsler Intelligence Scale for Children - Fourth Edition. FSIQ = Full-scale IQ score. PRI = Perceptual Reasoning Index. PSI = Processing Speed Index. WMI = Working Memory Index. VCI = Verbal Comprehension Index. WIAT-II-A&NZ = Wechsler Individual Achievement Test-Second Edition. CC2 = Castles and Coltheart Test 2.
[a] Group difference between Developmental Dyslexic group and Age matched controls.
[b] Group difference between Developmental Dyslexic group and Reading matched controls.

1.1.1. *ADHD symptoms*

The short form of the parent-rated Conners - Third Edition (Conners, 2008) assessed ADHD symptoms. This measure has good test-retest reliability, r = .89 (Conners, 2008). Six subscales measuring inattention, hyperactivity/impulsivity, learning problems, executive functioning problems, defiance/ aggression and peer relations were obtained with standardised *T*-scores based on normative data for age and gender used (M = 50, SD = 10). Scores above 70 (+2 SDs above the mean) were considered 'very elevated'.

1.1.2. *Socioeconomic status*

The Hollingshead Four-Factor Index of Socioeconomic Status (Hollingshead, 1975) was used to estimate the socioeconomic status of a child's family based on four domains: marital status, employment, education and occupation. Scores were computed for each parent by summing their occupation score multiplied by 5, and their education score multiplied by 3, with scores ranging from 8 to 66 (higher scores indicated higher socioeconomic ranking). Scores for two-parent families were taken as the average and individual scores were used for single-parent families. This measure has excellent test-retest reliability, r = .96 (Cirino, Sevcik, Wolf, Lovett, & Morris, 2002).

1.1.3. *Reading profile*

The Castles and Coltheart Test 2 (CC2) assessed lexical and sublexical abilities (Castles & Coltheart, 1993; Castles et al., 2009). It comprises 165 words, a list of 55 nonwords (e.g., nonsense words such as 'gop') that can only be successfully read through the sublexical pathway, a list of 55 irregular words (e.g., 'yacht') that can only be read via the lexical route, and a list of 55 regular words that can be read accurately by a combination of both routes. The regular and irregular words are matched on frequency, length and grammatical class. The nonwords also vary in their length and in the complexity of the grapheme-phoneme translations. The test has been re- ported to have excellent test-retest reliability for regular words, r = .93, and irregular words, r = .94 and good reliability for nonwords, r = .80 (McArthur et al., 2015). Participants read words aloud one at a time randomly presented from lists which increased in difficulty. Discontinuation occurred for a list when 5 consecutive errors were made with the test completed when either the child completed or discontinued on all three lists. Responses were audio-recorded to allow for double scoring.

Reading profile score was calculated as the ratio of the total number of items accurately read from the nonword and irregular lists, divided by the total number of items in each list: (raw score nonword-raw score irregular)/55. Scores ranged from -1 to +1. Negative values reflected better irregular word readers (i.e., poorer relative sublexical skills), whereas positive values reflected better nonword readers (i.e., poorer relative lexical skills). Larger numbers indicated greater disparity between sublexical and lexical skills.

1.2.3. Visual attention

Visual attention was assessed with the Combined Test of Visual Attention (CombiTVA; Vangkilde, Bundesen, & Coull, 2011) based on the estimation of parameters within the TVA framework proposed by Bundesen, 1990. The CombiTVA paradigm is open-sourced, available at https://github.com/ crsh/combitva (Papenberg & Aust, 2014). The CombiTVA has good test-retest reliability ranging between r = .75 to .85 across all parameters (Habekost et al., 2014). A novel version of the task was developed for the current study to utilise a selection of letter-like symbols as stimuli (Ѫ4┤ F╖ ɣжЂ Л ю l̲ƌ ʊ ɤ z), in addition to the letter stimuli employed in the original paradigm (BDEFHJKMNOPSTVX). Letter-like symbols were obtained from the extended American Standard Code for Information Exchange (ASCII) database and matched to alphabetical letters for visual complexity, calculated using the perimetric complexity measure (Pelli, Burns, Farell, & Moore-Page, 2006). Both versions of the paradigm were presented using E-prime 2 professional software (Psychology Software Tools) with participants seated in a semi-dark room approximately 60 cm from the 12 x 16-inch computer monitor (1024 x 768 pixel screen resolution, 100hz refresh rate). Participants completed versions of the task sequentially, with order of task (letters and symbols) counterbalanced.

For each trial, participants initially fixated on a central cross and were presented with one of three stimulus arrays (two targets; six targets; four targets and two distractors) displayed on an imaginary circle around the fixation cross (r = 7.5 degrees of visual angle), with six possible stimulus locations. Arrays with six targets were presented at each of six stimulus durations whereas both the two target arrays (with and without distractors) were shown for 80 ms. After presentation, arrays were terminated by a visual mask made from red and blue fragments completely covering the six stimulus locations to control for the effective exposure duration of the stimuli by preventing further processing in iconic memory stores. Participants then made an un-speeded report of all the red target letters/symbols they were confident of having seen. Participants responded by typing the letters/symbols in any order via a keyboard. Symbols were printed on adhesive stickers and placed on top of corresponding letters on the keyboard such that each symbol was always placed in the same location for all participants. Participants were told that their response speed was irrelevant and to refrain from guessing. They were encouraged to keep their reports within an accuracy range of 80 - 90%. The different trial types were presented in a randomised fashion in 9 separate blocks, each comprising 36 trials. All participants completed a practice block followed by a total of 324 trials for each version of the paradigm (648 trials in total). See Fig. 2 for a trial schematic.

Estimation of TVA components was conducted using the libTVA toolbox and MATLAB scripts adopting a previously developed maximum likelihood fitting procedure to model performance of all participants based on the TVA framework (see Dyrholm, Kyllingsbæk, Espeseth, & Bundesen, 2011). Grounded in the basic equations of the TVA, a participant's accuracy for both letter and symbol versions was modelled by a separate exponential growth function, based on the effective exposure duration. Maximum likelihood fitting procedures were conducted using the LIBTVA toolbox for MATLAB (R2016b; Bundesen, 1990; Bundesen, Habekost, & Kyllingsbaek, 2005; Kyllingsbaek, 2006) publicly available at http://www.machlea.com/mads/libtva.html.Five distinct components of visual attention were estimated: (1) VSTM capacity measured by the maximum number of targets accurately reported; (2) processing speed measured as the rate of visual targets processed per second; (3) perceptual threshold measured as the longest ineffective exposure duration in milliseconds; (4) top down control defined as the ratio between the attentional weight of a distractor and target (a value close to zero reflected efficient selection of targets while values close to 1 indicated no prioritising of targets compared with distractors); and (5) attentional weight, which indicated whether attentional weighting of objects averaged across targets and distractors was equal in the left and right visual hemifields (a value of .5 reflected equal attentional weighting across hemifields, <.5 reflected a right hemifield bias, and >.5 indicated a left hemifield bias). The model employed had 13 degrees of freedom (df): VSTM capacity = 5 dfs (reported as the expected capacity given a particular distribution of the probability that on a given trial VSTM capacity = 1, 2, …, 6); Processing speed = 1 df; Perceptual threshold = 1 df; Top-down control = 1 df; and attentional weighting = 5 dfs (one weight estimated for each of the six stimulus locations under the restriction that the relative weights sum to 1).

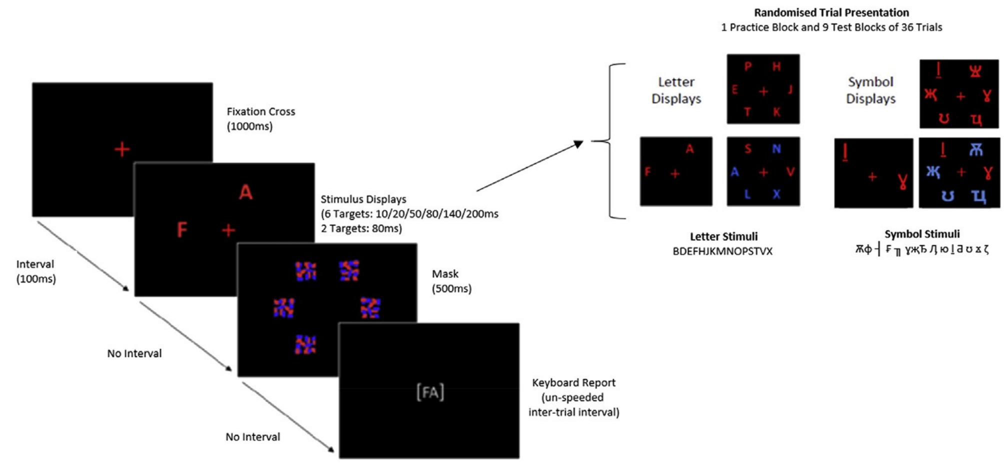

Fig. 2. CombiTVA trial schematic with examples of letter and symbol stimuli displays.

2.4. *Statistical analyses*

Group comparisons were first conducted to examine whether the DD group performed differently to either the AM or RM control groups across TVA components, and whether differences were seen across the letter and symbol stimulus conditions (see Table 2). A series of two-way mixed model ANOVAs were conducted with the five TVA components as the dependent variable to examine the effect of group (DD group, AM and RM controls), stimulus condition (letters and symbols) and their interaction. Where a main effect of group was identified following Bonferroni corrections, planned contrasts tested differences between the DD group and AM controls, and the DD group and RM controls, respectively. Moderation analyses were then performed for the TVA measures for which group differences existed, to determine whether differences were driven by participants with a specific reading profile (relatively poorer lexical or sublexical skills), or if performance was consistent, irrespective of reading profile. Where moderation was found, the Johnson-Neyman technique revealed the true zone of significance, identifying the precise level of the reading profile at which the relationship between word reading ability and the respective TVA component became statistically significant (Hayes, 2013). All analyses were run in IBM SPSS Statistics Version 25. The PROCESS macro was used for moderation analyses (Hayes, 2013) with the HC3 (Davidson-MacKinnon) heteroscedasticity-consistent inference applied. No part of the study analyses was pre-registered prior to the research being conducted. The conditions of ethics approval did not permit public archiving of anonymised study data. Readers seeking access to the data should contact the lead author or the local ethics committee at the Department of Ethics at Monash University. Access can be granted only to named individuals in accordance with ethical procedures governing the reuse of clinical data.

3. Results

3.1. *Group comparisons*

3.1.1. *VSTM capacity*

There was no main effect of group however, there was a main effect of stimulus condition whereby VSTM capacity was significantly higher (i.e., larger capacity) in the letter compared to the symbol condition. There was no significant interaction.

3.1.2. *Processing speed*

There was a main effect of group with contrasts revealing that the DD group had significantly slower processing speed than the AM controls, mean decrease of 5.11 items, 95% CI [1.920, 8.308], p = .002. However, there was no difference between the DD group and RM controls for processing speed, mean decrease of .50 items, 95% CI [-4.003, 3.011], p = .779. There was also a main effect of stimulus condition whereby processing speed was faster for the letter compared to the symbol condition, but there was no significant interaction between group and stimulus condition.

3.1.3. Perceptual threshold

There were no main effects of group, stimulus condition, or interaction between group and stimulus condition.

3.1.4. Top-down control selectivity

There were no main effects of group, stimulus condition, or interaction between group and stimulus condition.

3.1.5. Attentional weight

There was no main effect of group. A trend towards significance was seen for the main effect of stimulus condition, however this did not survive multiple comparison correction. There was no significant interaction.

3.2. Moderation analyses

The overall moderation model for processing speed in the letter condition was significant, F (3,51) = 12.15, p < .001, R2 = .488. Both word reading ability and reading profile uniquely predicted processing speed in the letter condition, b = .314, t = 2.16, p = .035, 95% CI [.023, .605] and b = -254.743, t = -2.36, p = .022, 95% CI [-471.717, -37.769], as did the interaction between word reading ability and reading profile, b = 2.376, t = 2.10, p = .041, 95% CI [.106, 4.646], indicating that the relationship between word reading ability and processing speed differed for participants based on their reading profiles. Simple slopes analyses revealed that the relationship between word reading ability and processing speed was only significant for those with a reading profile indicative of equivalent or poorer relative lexical skills (estimated at .0245 and .1943 respectively), b = .372, t = 2.92, p = .005, 95% CI [.116, .628] and b = .775, t = 4.90, p < .001, 95% CI [.458, 1.093]. The Johnson-Neyman technique specified that the zone of significance began at a reading profile of 2.0145 (i.e., either the same number of nonword and lexical words read accurately, or more nonwords read correctly; see part A of Fig. 3). The overall moderation model for the symbol condition was significant, F (3,51) = 11.92, p < .001, R2 = .319, reading profile alone predicted processing speed in the symbol condition, b = 46.694, t = 2.64, p = .011, 95% CI [11.231, 83.085], however, neither word reading ability, nor the interaction between reading profile and word reading ability were significant predictors, b = .027, t = .79, p = .432, 95% CI [-.041, .095] and b = -.379, t = -1.89, p = .064, 95% CI [-.780, .023], respectively (see part B of Fig. 3).

Table 2. Descriptive statistics and ANOVA results for TVA components across groups and stimulus conditions

Component	Developmental Dyslexic Group		Age matched Controls		Reading matched Controls		
	Letters	Symbols	Letters	Symbols	Letters	Symbols	
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	
VSTM Capacity	2.35 (.56)	1.44 (.33)	2.43 (.87)	1.29 (.30)	2.22 (.56)	1.43 (.50)	
							Group
							Stimulus
							Interactio
Processing Speed	20.65 (12.42)	6.41 (3.33)	27.73 (13.00)	9.55 (3.40)	19.87 (6.53)	6.18 (2.62)	
							Group
							Stimulus
							Interactio
Perceptual Threshold	28.96 (11.70)	30.96 (17.63)	30.37 (11.68)	27.21 (12.27)	30.48 (10.21)	28.06 (7.98)	
							Group
							Stimulus
							Interactio
Top-down Control Selectivity	.57 (.25)	.63 (.43)	.53 (.26)	.57 (.30)	.83 (.36)	.63 (.38)	
							Group
							Stimulus
							Interactio
Attentional Weight	.48 (.18)	.52 (.22)	.52 (.26)	.58 (.22)	.51 (.19)	.57 (.24)	
							Group
							Stimulus
							Interactio

Note. * = $p < .05$. ** = $p < .001$. ǂ = significant following Bonferroni corrections.

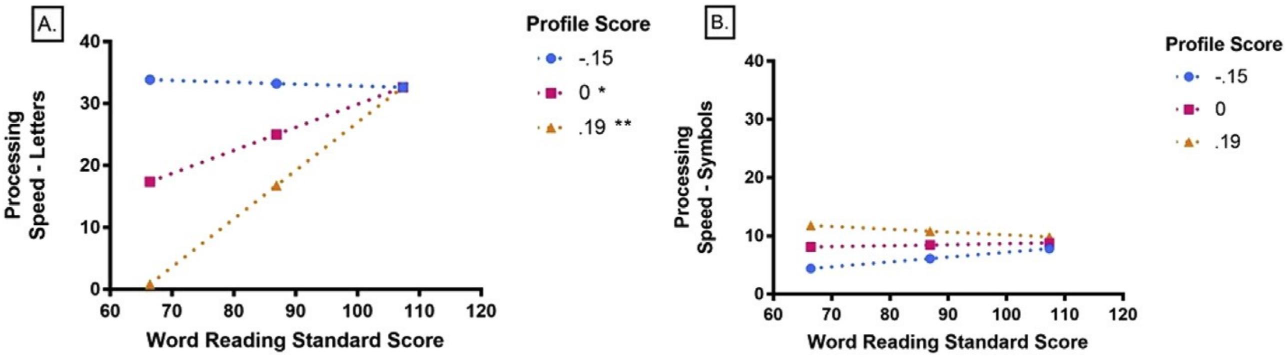

Fig. 3. The relationship between word reading ability (Word Reading Standard Score) and processing speed (seconds) for the DD and AM controls for the letter (A) and symbol (B) conditions, as moderated by reading profile estimated at -.15 (poorer relative sublexical skills), 0 (equivalent sublexical and lexical skills) and +.19 (poorer relative lexical skills), indicating a discrepancy of 8, 0 and 10 words respectively. Estimates obtained using ±1 SD from the mean of predictor variable as per Hayes (2013). * = $p < .05$. ** = $p < .001$.

2. Discussion

The current study not only confirms the utility of the TVA framework as an informative tool for investigating visual attention in DD, it is the first to use non-linguistic stimuli to assess generalisability of deficits within this strong computational model of attention. It was also novel in employing comparisons of children with DD to controls matched on reading ability, in addition to the traditional age matched methodology and examining how the relationship between measures of visual attention and reading ability vary as a function of individual differences in reading profile.

Visual attention was first examined on a group level to confirm previously reported patterns in the TVA literature of DD employing age matched control comparisons, and to determine if deficits were unique to individuals with DD after controlling for reading ability. As hypothesised, children with DD performed similarly to both their age matched and their reading matched peers in terms of their perceptual threshold, attentional weighting, top-down control and VSTM capacity. These findings are broadly consistent with past TVA research in DD. Neither, Dubois et al. (2010) nor Bogon, Finke, and Stenneken (2014) found impairments in perceptual threshold, laterality of attentional weighting or top-down control in their samples of children with DD. Although Stenneken et al. (2011) reported an absence of typical leftward attentional bias in their adult DD sample, our data shows symmetrical attentional allocation in the DD and both control groups, adding weight to the notion that a left bias may typically arise with development into adulthood (Chung, Liu, & Hsiao, 2017). In contrast to the findings of Bogon, Finke, and Stenneken (2014) and, in part, Dubois et al. (2010) where VSTM capacity was shown to be reduced at least for some children with DD, our results did not suggest a significant reduction for our DD sample. Instead, our findings are more consistent with those of Stenneken et al. (2011) where high- achieving adults with DD performed comparably to age matched peers. However, intact VSTM capacity in our sample of children with DD of average intellect casts doubt on VSTM capacity being a potential marker for the ability to offset difficulties with intellect, initially proposed to explain these differences across child and adult samples (Gathercole & Pickering, 2000). Instead, given that past findings were mixed with only some DD participants showing poorer than expected VSTM capacity, it is more likely that other factors, such as ADHD symptomatology (Low et al., 2018; Shanahan et al., 2006), also impact VSTM capacity as measured by TVA independently of reading ability (Finke et al., 2011). Further work is needed however, to clarify the nature of these related factors to ascertain how they influence performance on TVA measures and could potentially explain mixed findings across DD samples. Nevertheless, our sample did not present with any prominent VSTM capacity impairments.

As expected, DD in our cohort was associated with markedly reduced processing speed, relative to AM controls. This confirms the most consistent finding in past TVA research showing that those with DD are slower in processing visual information than their same-aged, typically reading counterparts. Furthermore, since deficits were not observed for other TVA parameters, poor processing speed on the TVA task appears to be a specific and isolated deficit in DD. Therefore, reduced VAS in DD cohorts is likely to be driven by reduced efficiency in processing visual material. At face value, the finding that those with DD are slower at processing visual material than their same-age peers, aligns with a variety of theories purporting deficits in the speed or automaticity of multi-element processing (Denckla & Rudel, 1975; Fawcett, Nicolson, & Dean, 1996; Hari & Renvall, 2001; McLean, Stuart, Coltheart, & Castles, 2011). Notably however, processing speed was equivalent when comparing DD participants with RM controls, indicating equivalent performance when reading ability was accounted for. As such, poor visual processing speed is unlikely to be a unique deficit, fundamentally contributing to the reading difficulties experienced by all individuals with DD.

This study also investigated whether attentional deficits in the DD sample were global in that they applied to novel, non-linguistic stimuli in addition to familiar letters. Results revealed no differences in performance for our DD sample or either of our control groups on attentional weight, perceptual threshold or top-down control measures across stim- ulus conditions. However, there were differences for VSTM capacity and processing speed, with poorer performances on the symbol version of the task. For processing speed in particular, the reduction in performance was profound with a drop of approximately 65e70% across all groups. Therefore, the ability to name or verbalise stimuli did not impact on the minimum exposure time for perception, the ability to allocate attention across space or to inhibit distractors and identify targets. It did, however, impact the maximum number of items that could be held in VSTM stores, and how quickly stimuli could be processed, irrespective of reading ability. That performance was worse for the symbol compared to the letter condition is consistent with past studies showing that humans process familiar stimuli such as letters and numbers faster and differently from non- letters (Burgund & Abernathy, 2008; Maurer, Brem, Bucher, & Brandeis, 2005; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999) and is similar to interpretations offered by Ziegler et al. (2010) as well as Collis et al. (2013). In addition, the ability to maintain more letters than symbols in VSTM stores is in keeping with well-accepted models of working memory whereby stimuli that can be rehearsed verbally in an articulatory feedback loop as well as visually via a visuo-spatial sketchpad can be maintained more easily than stimuli that can be sustained in only one modality (Paulesu, Frith, & Frackowiak, 1993). In visual attention terms, this would mean that more attention has to be allocated for the processing of each non-familiar item to reach an equivalent identification threshold, which would reduce the number of accurately identified items as compared to familiar stimuli (Wang & Gillebert, 2018).

Although all participants demonstrated reduced VSTM capacity and speed on the symbol compared to letter version of the TVA task, neither group did more so than the other (i.e., there was no interaction effect). Even expert readers have been shown to be poor at identifying arrays of visually unfamiliar items under brief presentation times (Shovman & Ahissar, 2006; Ziegler et al., 2010). As group differences for processing speed were observed across both letter and symbol versions of the TVA, we infer a domain general processing speed deficit for those with DD. While studies have assessed multi-element processing in DD across different stimulus conditions previously, reported findings are largely mixed. Some demonstrate specific deficits only in processing of letter, digit or colour arrays without equivalent impairments for symbols, thought to reflect deficits in mapping visual stimuli to phonology, consistent with the phonological deficit hypothesis of DD (Collis et al., 2013; Ziegler et al., 2010). On the other hand, there is also research that shows consistent performances in DD samples for both letters, symbols and pseudo-letters (Fernandes, Vale, Martins, Morais, & Kolinsky, 2014; Hawelka & Wimmer, 2005; Romani, Tsouknida, di Betta, & Olson, 2011; Shovman & Ahissar, 2006; Valdois et al., 2012). Consistent with these latter findings, the current results add weight to the notion that processing speed deficits in those with DD compared to AM controls lie in the visual aspect of processing, and not in an inability to map and rapidly recall phonological information for familiar stimuli. Additional strengths of our design were that symbols were specifically matched to letters for visual complexity and that the TVA paradigm requires participants to produce un-speeded, motor responses, thereby reducing the need to rapidly access phonological information.

This study also asked whether reading profile accounted for individual differences in processing speed performance. The results here indicated that although the DD group performed significantly slower than the AM group overall, the relationship between processing speed and reading ability was moderated by reading profile for the letter condition. That is, the relationship between processing speed and reading ability was only significant for those with a mixed or positive reading profile, indicative of equivalent or poorer relative lexical skills (i.e., mixed or lexical dyslexics). For this subset of participants specifically, processing speed was significantly poorer for letters in the DD group compared to the AM controls. Additionally, as the discrepancy between lexical and sublexical skills increased (i.e., greater relative impairments in lexical skills), processing speed further declined. In comparison, there was no significant relationship between reading ability and processing speed for those with a negative reading profile indicative of better lexical relative to sublexical skills (i.e., sublexical dyslexics), signifying similar performance to typically developing peers, despite their reduced reading ability overall. The prominent slowing in processing speed in those with DD who present with lexical deficits is characteristic of those with difficulty in the fast and automatic access to whole words (Ziegler et al., 2008). It also accords with prior research showing that VAS abilities have a greater impact on irregular word reading than phonological skills (Bosse & Valdois, 2009). Notably, reading profile was not a significant moderator for supplementary analyses conducted with reading matched controls (see supplementary material), nor was it significant for the symbol condition. This suggests that the same performance patterns were seen across the continuum of reading profiles when compared with younger, typically developing readers for both stimulus conditions. However, reading profile was then relevant when comparisons were made to same-age peers. This suggests those with relative lexical impairments continue to perform at levels equivalent to younger readers, while those with relative sub-lexical difficulties and typical readers make continued gains. As this moderation effect only held when speed was measured with letters, it seems that reading profile is only relevant when assessing processing of linguistic material. Accordingly, although on the whole the DD group was slower for both letters and symbols indicating a domain general speed deficit, it appears that individuals with relatively poorer lexical skills demonstrate a more pronounced letter-specific speed impairment when compared with same-age peers and drive group differences in this domain. We speculate that this is because children with relatively poorer lexical skills present with difficulties in acquiring automaticity in their reading that may only be evident when this is relied upon at later stages of reading development. This interpretation is strengthened by research showing that typical reading acquisition usually be- gins with a greater reliance on sublexical strategies with increased recruitment of lexical strategies as reading proficiency improves with age (Sprenger-Charolles, Siegel, Jime nez, & Ziegler, 2011). Combining this with the previous evidence of equivalent speed performances to reading matched controls, it appears that lexical dyslexics specifically experience a failure to refine attentional skills for reading to the same degree as their peers. Importantly, this may explain why mixed findings are so commonly reported in the DD literature across stimulus modalities.

The finding that only a subset of individuals with DD demonstrated processing speed differences has important clinical translation value for DD. Recently, Valdois et al. (2019) demonstrated that distinct sub-systems of visual attention can be dissociated neuroanatomically in a stroke patient with bilateral superior parietal lobe damage who displayed specific VAS impairments but preserved attentional shifting. This profile was argued to reflect distinct impairments in the endogenous dorsal, but not ventral, attentional network (Corbetta & Shulman, 2002) which may provide a neuroanatomical analogue for global processing in the MTM model. Valdois and colleagues discuss these results in the context of DD, suggesting that individuals who display deficits in VAS but preserved phonological skills, akin to our mixed and lexical dyslexics demonstrate differential visual processing speed impairments (Peyrin, De monet, Baciu, LeBas, & Valdois, 2011, Peyrin et al., 2012). The lexical dyslexics in our case may therefore suffer from specific dysfunction of the superior parietal lobes that affects letter processing more prominently (see also Lobier et al., 2014). Therefore, it may be that attentional immaturity, resulting in poorer processing speed, reflects dysfunctional development of the superior parietal lobes but only for this subset of individuals. We do note however, that given our subset of lexical dyslexics were similar in terms of the degree of their poor reading to sub- lexical dyslexics, this line of thinking would predict the same degree of impediment to attentional refinement across all reading profiles if poor processing speed purely arose as a result of their reading difficulties. Instead, for those with relatively poorer lexical skills it is likely that the VAS difficulties characterising this particular subset of DD are the result of a more dynamic relationship between reading and attention (Cestnick & Coltheart, 1999). The literature also suggests that attentional shifting may be specifically linked to sublexical route efficiency (Facoetti et al., 2010) and therefore may be more relevant than VAS for our children with relative sublexical deficits. We do note however, that there is evidence VAS may be important for sublexical reading in other languages such as French, so delineation of visual attention skills based on distinct reading profiles as demonstrated here may be specific to English readers (Zoubrinetzky et al., 2014). Regardless, the evidence that not all of those with DD present with equivalent attentional difficulties speaks strongly to the importance of characterising individual strengths and weaknesses, providing impetus for clinicians to tailor assessments to enable identification of those with DD who are at-risk of developing attentional difficulties and providing intervention early. In fact, attentional training studies making use of action video games for reading remediation in DD (Franceschini et al., 2013; Franceschini et al., 2015; Gori et al., 2013; see Peters, De Losa, Bavin, & Crewther, 2019 for a recent review) may be most suitable for those with relatively poorer lexical skills.

There are some limitations of the current study that provide avenues for future research. We acknowledge that matching participants on a single measure of reading ability fails to consider the range of reading skills (e.g., reading speed, fluency and spelling) and greater sample sizes would ensure increased power. Although we recognise that this adds to the recruitment burden, future research capturing reading ability more comprehensively will ensure a more tightly controlled matching methodology. This is particularly important as processing speed on TVA tasks has been linked to reading speed in both typical and atypical readers and may therefore play a role in reading beyond single word reading accuracy (Lobier et al., 2013). Further, characterising reading profile as relative lexical to sublexical skills does not account for what is considered typical variation in these skills. There are, however, significant advantages to capturing reading skills along a continuum, including ensuring that participants presenting with different abilities are not crudely clustered to form discrete sub-groups, and that the relative contribution of both pathways are considered, matching more closely to the DRM. However, further research is needed to validate the use of relative lexical and sublexical skills as a single indicator of reading profile, and to establish the points at which skill discrepancy indicates either superiority or deficiency. Moreover, although reductions in speed and VSTM capacity for symbols were commensurate across groups, performance was significantly reduced on the symbol condition implying that perhaps the stimuli used were too complex to fully process given the short exposure durations of TVA. Although a matching procedure was conducted to ensure symbols were visually equivalent to letters, it would be worthwhile exploring the use of other forms of novel stimuli, including nameable symbols, within the TVA framework to confirm generalisability of deficits across in DD samples. There are also inherent limitations of the paradigms used to assess multi-element processing as they do not require accurate report of both stimulus identity and position. However, coding of relative letter location is critical for orthographic processing during reading. While the results of this study suggest our DD group accurately reported stimuli across spatial locations similarly to controls, future studies investigating multi- element processing in DD should seek to adapt tasks to better mimic reading processes by requiring participants to also indicate stimulus position as attempted by Starrfelt, Petersen and Vangkilde (2013).

4. Conclusions

The current study extends on previous work examining visual attention in DD within the TVA framework. Although slowed processing speed was shown to differentiate those with DD from their same age peers across both letter and symbol stimuli, these deficits were not unique after accounting for reading ability. Our results also revealed that group differences were driven by a smaller subset of individuals with either equivalent or poorer relative lexical skills (mixed and lexical dyslexics), suggesting that processing speed deficits index reading immaturity in this subset of individuals specifically. This study highlights the complex role reading plays in the refinement of supplementary cognitive networks such as visual attention and emphasises the importance of accounting for heterogeneity in DD samples. Further research is needed to confirm the findings here by establishing the nature of the relationship between visual attention, in particular processing speed, and reading longitudinally both for typical and atypical readers. Neuroimaging work examining the interplay between reading and attentional networks within the brain would also help to provide a neurobiological basis for these findings.

Conflict of interest

None declared.

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Open practices

The study in this article earned an Open Materials badge for transparent practices. Materials and data for the study are available at http://www.machlea.com/mads/libtva.html.

CRediT authorship contribution statement

Nicole Stefanac: Conceptualization, Methodology, Project administration, Data curation, Formal analysis, Writing - original draft. **Megan Spencer-Smith:** Conceptualization, Supervision, Writing - review & editing. **Meadhbh Brosnan**: Conceptualization, Software, Formal analysis, Writing - re- view & editing. **Signe Vangkilde**: Methodology, Writing - re- view & editing. **Anne Castles**: Conceptualization, Writing - review & editing. **Mark Bellgrove**: Conceptualization, Funding acquisition, Resources, Supervision, Writing - review & editing.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2019.08.004.

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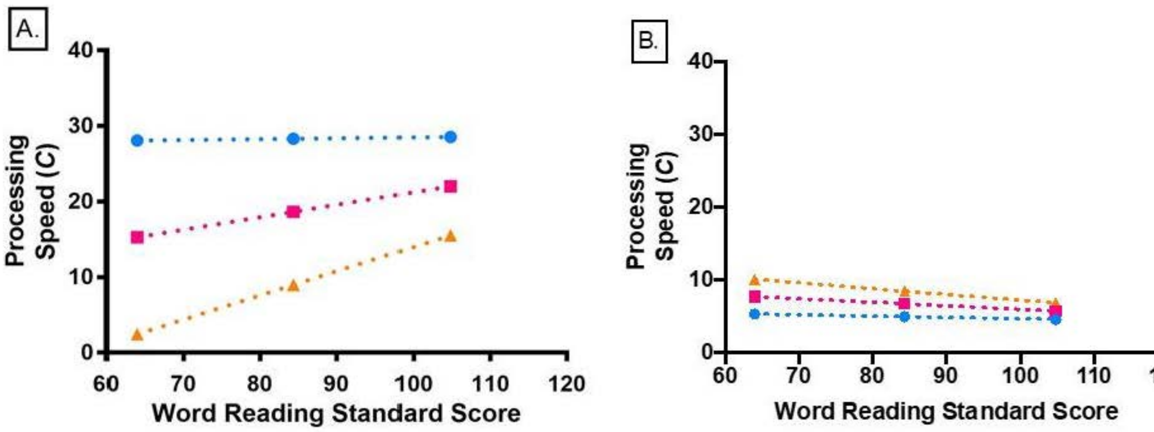
Supplementary Material



Supplementary Figure 1. The relationship between word reading ability (Word Reading Standard Score) and proce
symbol (B) conditions for the DD and RM groups, as moderated by reading profile estimated at -0.15 (poorer relativ
and lexical skills) and +0.14 (poorer relative lexical skills), indicating a discrepancy of 8, 0 and 7 words respectiv
the mean of predictor variable as per Hayes (2013). As demonstrated, reading profile was not a significant mo
conditions, indicating that processing speed performances did not vary as a function of relative lexical or sublexica

Appendix A

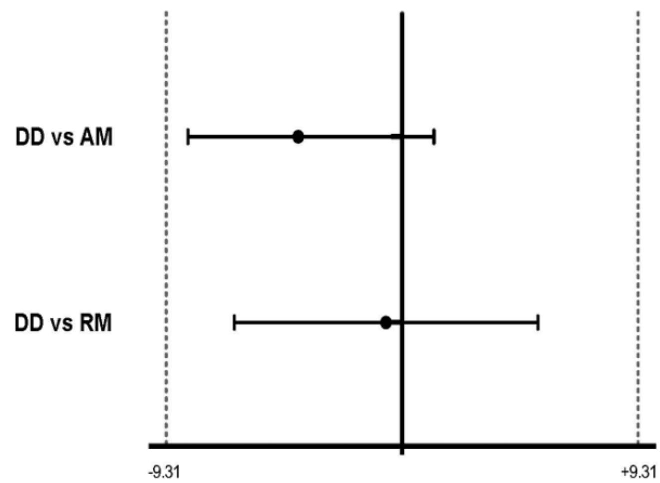


Figure A1. Whisker plots depicting 95% CI of mean differences between the Developmental Dyslexia (DD) a
Reading Matched (RM) control groups for *T*-scores on the inattention sub-scale taken as the reliable change i
As per the manual, *T*-score differences of greater than 9.31 are considered clinically significant. In this case,
within the 'average' range and are therefore deemed clinically equivalent (Mara & Cribbie, 2012; Cribbie &

Appendix B

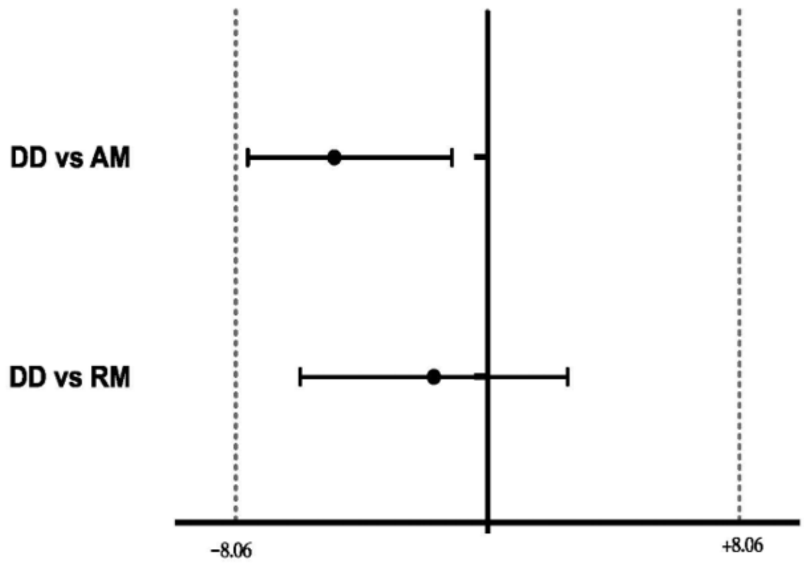


Figure A2. Whisker plots depicting 95% CI of mean differences between the Developmental Dyslexia (DD) a
Reading Matched (RM) control groups for *T*-scores on the hyperactivity/impulsivity sub-scale taken as the re
Conners (2008). As per the manual, *T*-score differences of greater than 8.06 are considered clinically signific
were rated as being within the 'average' range and are therefore deemed clinically equivalent (Mara & Cribb
2009).

Appendix C

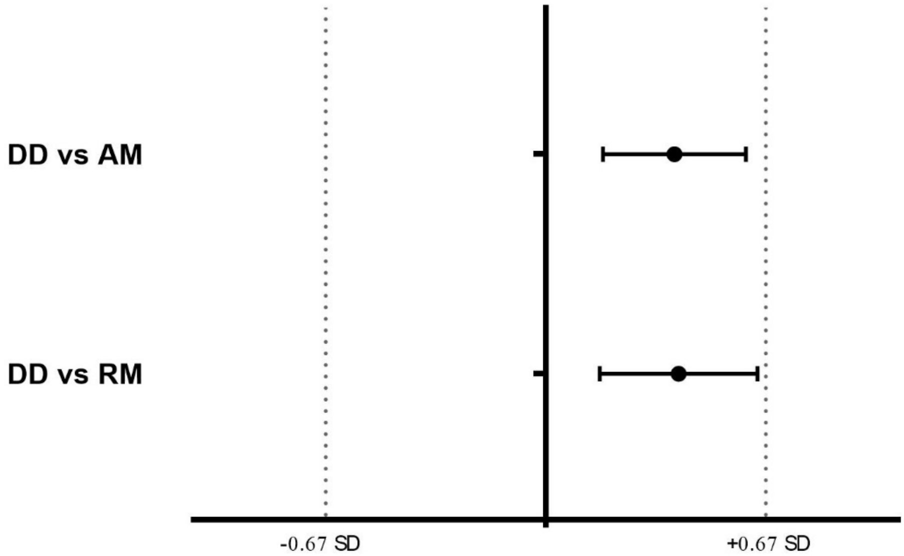


Figure A3. Whisker plots depicting 95% CI of mean differences between the Developmental Dyslexia (DD) a Reading Matched (RM) control groups for FSIQ Index score taken as the reliable change index according to manual, score differences greater than 0.67 of a standard deviation are considered clinically significant. In thi as being within the 'average' range and are therefore deemed clinically equivalent (Mara & Cribbie, 2012; Cr

CHAPTER SEVEN: INNEFFICIENT EVIDENCE ACCUMULATION IN CHILDREN WITH DYSLEXIA UNDERLIES SLOW PERCEPTUAL DECISION MAKING

Preamble

Typically, the paradigms used to measure visual processing in studies of DD require a perceptual decision to be made about a stimulus (i.e., the presence or absence of a target), with outcomes assessed using performance metrics such as reaction time and accuracy. However, these measures are relatively crude indicators of complex underlying cognitive processes. There are several processes involved in converting perception of visual material into a corresponding physical action (Gold & Shadlen, 2007). Thus, patterns of poor performance on tasks commonly interpreted to reflect visual attention dysfunction in DD may arise due to different underlying deficits with perceptual decision making.

Event-related potentials (ERPs), derived from electroencephalographic (EEG) data, are measures that can provide millisecond-by-millisecond measures of stimulus processing and permits tracking of the fast, cognitive processes involved in perceptual decision making (Luck, 2005). The current study exploited these benefits to isolate neural markers corresponding to discrete stages of attending to, processing and making a decision about visual motion stimuli in children with DD. The aim was to ascertain the precise neural signatures corresponding to poor outward task performance usually interpreted as either sensory or visual attention dysfunction in DD. This study also examined whether any detected deficits were unique to DD, or if they were related to reduced reading experience by employing age and reading matched comparisons as well as investigating whether deficits varied as a function of reading profile.

This is the first study to identify that children with DD demonstrate disorder-specific slowing of perceptual decision making in response to motion stimuli which has a neural basis in dysfunctional evidence accumulation. Specifically, children with DD with relatively poorer lexical deficits demonstrated a reduced rate of evidence accumulation and reach attenuated decision making thresholds sooner but at the performance level they remain slow in their response. Accordingly, this study provides important evidence that children with DD inefficiently process visual information beyond initial orientation toward stimuli and sensory registration which is likely affecting how easily they are able to process written words as wholes via the lexical pathway. This study identifies a neural basis for poor perceptual decision making in DD likely associated with poor attentional engagement within magnocellular-dorsal pathway of visual processing.

Abstract

Visual processing deficits have been widely reported in the developmental dyslexia literature, yet the paradigms used typically require a decision to be made about a stimulus with outcomes measured behaviourally. Thus, behaviours such as slowed response times, may be attributable to dysfunction at one or more different stages of the decision making process in developmental dyslexia. Here, we utilized electroencephalography (EEG) recorded during a perceptual decision making task to identify the precise neural locus of any decision making deficits in developmental dyslexia. We also investigated whether presenting deficits were unique to children with dyslexia or if they were also evident in other, typically developing children with equally immature reading systems and if deficits varied as a function of individual reading profile. An initial pool of 217 children with dyslexia and 81 control children underwent neuropsychological screening to determine eligibility. The final sample included sixty-eight participants: 32 with dyslexia (DD; 16 females); 21 age matched controls (AM; 11 females) and 15 reading matched controls (RM; 9 females). All participants completed a bilaterally presented random-dot motion task while EEG was recorded. Event-related potentials reflecting low level sensory processing (steady state visual evoked potentials; SSVEPs), pre-target attentional bias (posterior α power), attentional orienting (N2), evidence accumulation (centro-parietal positive decision signal; CPP) and execution of a motor response (β) were obtained to index the temporal sequence of perceptual decision making. Reading profile was measured, providing a score of relative lexical and sublexical skills for each participant. Although all groups performed comparably in terms of task accuracy and false alarm rate, the DD group were slower and demonstrated an earlier peak latency, reduced slope and lower amplitude of the CPP compared with both AM and RM controls. Reading profile also moderated the relationship between word reading ability and reaction time as well as CPP indices, such that lexical dyslexics specifically responded more slowly and had a shallower slope, reduced amplitude and earlier latency of CPP waveforms. The results indicate that children with dyslexia, particularly those with relatively poorer lexical abilities, have a reduced rate of evidence accumulation and reach attenuated decision thresholds sooner but remain slow in their outward response. These data are in keeping with hypotheses that children with dyslexia have a fundamental impairment in effectively sampling and processing evidence about visual motion stimuli which results in impaired task performance.

Keywords: Developmental dyslexia; Attention; Decision making; Evidence accumulation; Neurodevelopment.

Abbreviations:

- AM = age matched
- CPP = centro-parietal positive decision signal
- DD = developmental dyslexic
- N2c = contralateral N2
- N2i = ipsilateral N2
- RM = reading matched
- SSVEPs = steady state visual evoked potentials

Introduction

Developmental dyslexia (hereafter referred to as dyslexia) is a neurodevelopmental disorder characterised by difficulties with accurate or fluent word reading. Although symptoms required for a diagnosis are circumscribed to below age-expected reading, individuals with dyslexia frequently present with a wide array of other deficits outside the domain of reading including dysfunction in how they process visual stimuli. There is increasing evidence that individuals with dyslexia present with difficulties processing visual stimuli at the sensory/perceptual level (Stein, 2001) and in higher-order attentional functions that guide what visual information is processed and when (Bosse, Tainturier, & Valdois, 2007; Collis, Kohnen, & Kinoshita, 2012; Facoetti & Molteni, 2001; Facoetti, Turatto, Lorusso, & Mascetti, 2001; Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012; Vidyasagar & Pammer, 2010). However, evidence for the primacy of these deficits is controversial, with mixed results frequently reported across studies (Ramus, 2003; Stein, 2018).

Typically, the research paradigms used to assess visual processing require a decision to be made about a visual stimulus, with outcomes measured behaviourally (e.g., response accuracy and/or reaction time). Accordingly, poor performances, commonly attributed to either sensory or attentional deficits in dyslexia, may arise from dysfunction at any point along the perception-to-action continuum. Yet, little effort has been dedicated to investigating the role that perceptual decision making may play in accounting for differences between individuals with dyslexia and their typically reading peers. Perceptual decision making encompasses multiple processing stages from perceiving visual stimuli, selecting features whilst inhibiting irrelevant information, mentally representing information and accumulating relevant evidence to prepare, initiate and execute subsequent motor actions (Gold & Shadlen, 2007; Joo, Katz, & Huk, 2016; Loughnane et al., 2016; Resulaj, Kiani, Wolpert, & Shadlen, 2009). Even the most elementary of sensorimotor decisions relies on the careful coordination of a range of skills to enact accurate and time-sensitive responses. Event-related potentials, derived from electroencephalographic (EEG) data, can provide a millisecond-by-millisecond measure of information processing flow from perception to action (Luck, 2005). For instance, researchers have identified event-related potentials indexing information flow across the perception to action hierarchy: low level sensory processing (steady state visual evoked potentials; SSVEPs), pre-target attentional bias (posterior α power), attention orienting (N2), evidence accumulation (centro-parietal positive decision signal; CPP) and execution of a motor response (β; Kelly & O'Connell, 2013; Loughnane et al., 2016; Newman, O'Connell, & Bellgrove, 2013; O'Connell, ckree, & Kelly, 2012). Importantly, using event-related potentials in this way may help to identify the locus of visual processing dysfunction in dyslexia and in turn, isolate the mechanisms that contribute to poor reading in dyslexia.

Beyond studies examining electrophysiological correlates in response to linguistic material or auditory stimuli, neural markers of visual perceptual decision making have not been extensively examined in dyslexia. Instead, researchers have focused on isolated stages of processing. At the forefront is research investigating motion detection and contrast perception (for reviews see Laycock, Crewther, & Crewther, 2008 and Schulte-Körne & Bruder, 2010). Here the most consistent findings are prolonged latencies and smaller amplitudes of typical visually evoked potentials (Laycock, Crewther, & Crewther, 2008; Schulte-Körne & Bruder, 2010) alongside dysfunctional lateralisation of components such as the N2 (Jednoróg, Marchewka, Tacikowski, Heim, & Grabowska, 2011) thought to reflect sensory impairments in magnocellular functioning. However, not all studies have found results consistent with magnocellular dysfunction (Johannes, Kussmaul, Münte, & Mangun, 1996; Victor, Conte, Burton, & Nass, 1993). Beyond early sensory detection, there is electrophysiological evidence to suggest that individuals with dyslexia orient their attention differently towards visual material (Wijers, Been, & Romkes, 2005), although this too has not always been supported with some arguing that the deficit instead lies in an inability to sustain visual attention (Van der Lubbe, de Kleine, & Rataj, 2019). More recently, behavioural evidence using drift diffusion modelling indicates that poor readers display suboptimal decision making (O'Brien, Joo & Yeatman, 2019) suggesting that processes beyond initial detection or perception of a visual stimulus may be impaired in dyslexia. However, the precise mechanism underlying this is yet to be examined. It therefore remains unclear whether visual processing deficits in individuals with dyslexia are driven by dysfunction in early attentional allocation or sensory detection of stimuli, or if difficulties are evident at later phases where information is processed, integrated with task requirements from top-down and a corresponding decision is made.

A significant issue in dyslexia research is that the direction of the relationship between reading and visual processing deficits is unclear. Although some researchers claim deficits in attending to and processing visual material can account for reading difficulties (Bosse et al., 2007; Facoetti & Molteni, 2001; Franceschini et al., 2012; Vidyasagar & Pammer, 2010), others have argued that differences between individuals with dyslexia and typically reading controls may be the consequence, rather than the cause, of poor reading (Goswami, 2015). This line of reasoning arises from evidence showing that learning to read has a flow on effect for visual and attentional abilities. For instance, reading habits such as orthographic direction have been shown to influence performance on visual attention tasks (Chokron & Agostini, 1995; Chokron & Imbert, 1993; Kermani, Verghese, & Vidyasagar, 2018). Accordingly, visual deficits may arise subsequent to reduced reading practice and suboptimal reading experience as supplementary visual and attentional skills are not refined to the same degree as in typically developing children. In this case, all children with immature reading systems would be expected to show visual deficits regardless of whether they meet age-expected reading benchmarks. Thus, there has been a call to supplement traditional age matched control comparisons with reading matched designs where participants with dyslexia are compared with younger, typical readers of equivalent reading ability (Goswami, 2003). Using such designs, researchers are able to effectively account for reading ability and determine whether deficits are unique to dyslexia or are evident in all children with immature reading abilities.

Individuals with dyslexia also frequently present with varying types of reading difficulties, further complicating the search for unique causal factors. Contemporary models posit that reading requires the contribution of two overall processing pathways, the *sublexical* (or phonological) and the *lexical* (or surface) routes, which differ in their contributions depending on word frequency and regularity (Coltheart, Curtis, Atkins, & Haller, 1993). Hence, individuals with dyslexia may present with reading profiles which vary considerably in terms of the relative strength/weakness of sublexical and lexical processes (Ziegler et al., 2008). Some individuals sit at either ends of the spectrum with marked dissociation of both lexical and sublexical skills (so-called *lexical* and *sublexical dyslexics* respectively*;* Castles, Bates, Coltheart, Luciano, & Martin, 2006; Castles, Datta, Gayan, & Olson, 1999) whereas the majority fall between these extremes (known as *mixed* dyslexics; Jackson & Coltheart, 2001).

There is evidence that different visual processing deficits may be specific to different types of dyslexic readers. For instance, poorer nonword readers (i.e., sublexical dyslexics) have been shown to exhibit reduced sensitivity to visual motion stimuli with low spatial frequencies at the sensory level (Borsting et al., 1996; Slaghuis & Ryan, 1999) and slower time courses for visual stimulus processing (Gori, Cecchini, Bigoni, Molteni, & Facoetti, 2014). Individuals with this reading profile have also been shown to exhibit longer response latencies in attentional masking paradigms (Franceschini et al., 2012; Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014) and poorer inhibition of visual targets in the right visual field indicative of a visuospatial leftward mini-neglect (Facoetti et al., 2006) compared to both control participants and other dyslexics with intact nonword reading. On the other hand, in lexical dyslexics, reduced visual attention span and rapid naming has been associated with reduced accuracy in their report of multi-object strings (Lassus-Sangosse, N'guyen-Morel, & Valdois, 2008). Despite this growing evidence, there are findings that show visual deficits are not consistently linked to a specific type of dyslexia (Lukov et al., 2015; Ridder, Borsting, & Banton, 2001). Thus, debate regarding differentiation of visual deficits on the basis of reading type continues. A significant drawback of past studies is the tendency to examine differences between discrete sub-groups of individuals with dyslexia who present with prominent deficits in one specific route of reading. Accordingly, past research has operated on the assumption that all individuals in these sub-groups are alike thus failing to account for individual variations across the spectrum of relative lexical and sublexical skills.

Here we utilised an EEG perceptual decision making framework to isolate distinct neural markers of the discrete stages of information processing that may contribute to cognitive deficits in dyslexia. The aims were threefold: (1) to isolate the neural markers underpinning the performance of children with dyslexia using a random dot motion paradigm; (2) to ascertain whether any deficits were unique to children with dyslexia or if they were associated with immature reading skills using comparisons to both age and reading matched controls; and (3) to investigate whether any identified deficits varied as a function of reading profile using a continuous measure of relative lexical and sublexical abilities. Although it was expected that as a group, children with dyslexia would respond more slowly compared with their typically reading peers, it was unclear whether this would be reflected in abnormal functioning in early or relatively later phases of perceptual decision making at the neural level. It was also unclear whether deficits would be unique to children with dyslexia or if they would be associated with a general underdevelopment of reading networks and therefore evident in both the dyslexic and reading matched groups. Given evidence of differentiation of visual processing deficits across different types of dyslexia, it was predicted that perceptual decision making deficits would vary on the basis of reading profile.

Materials and Methods

Participants

An initial pool of 217 participants with dyslexia was recruited from local paediatric clinics specialising in the assessment of learning difficulties, as well as community support groups for parents of children with academic challenges. Eighty-one control participants were recruited from local schools and the community via advertisements. Interested participants were deemed eligible if they were right-handed, aged between 8-16 years, reported normal or corrected to normal vision, normal hearing, no history of developmental delay, attention-deficit hyperactivity disorder (ADHD), intellectual disability, autism spectrum disorder, behavioural or emotional disorders, and no known neurological history including head injury with loss of consciousness. The dyslexia sample was required to have a diagnosis of specific learning disorder in reading by a psychologist or neuropsychologist, according to current Diagnostic and Statistical Manual of Mental Disorders (DSM-5) criteria, but no other comorbid diagnoses. Control participants had no history of any learning difficulties or delays.

Neuropsychological screening was conducted to confirm the absence of intellectual disability (Full-scale Intelligence Quotient < 70) and parent-reported elevated symptoms of ADHD (scores within the 'very elevated' range for either the inattention or hyperactivity/impulsivity sub-scales of the Conners 3). The presence of reading difficulties in the dyslexia sample was confirmed (score at least 1.5 standard deviations below age-appropriate levels on the word reading subtest on the Wechsler Individual Achievement Test -

Second Edition). Control participants performed within ±1 standard deviation of age-corrected means for word reading, indicative of age-appropriate reading ability. Test scores were accessed for two participants in the dyslexia sample who had undergone neuropsychological assessment within the preceding 12 - 18 months. Neuropsychological results were also used to match control participants to the dyslexic sample on the basis of either chronological age (age matched; AM controls) or reading age (reading matched; RM controls). Independent samples t-tests confirmed the absence of statistical differences on key matching variables. No differences were seen for the DD group and AM controls in terms of chronological age, $t(51) = -0.04$, $p = .972$, 95% CI [-0.85, 0.82] and no significant differences were seen for the DD group and RM controls for reading age, $t(45) = 1.32$, $p = .195$, 95% CI [-0.16, 0.77]. See Fig. 1 for flow of participants through this protocol.

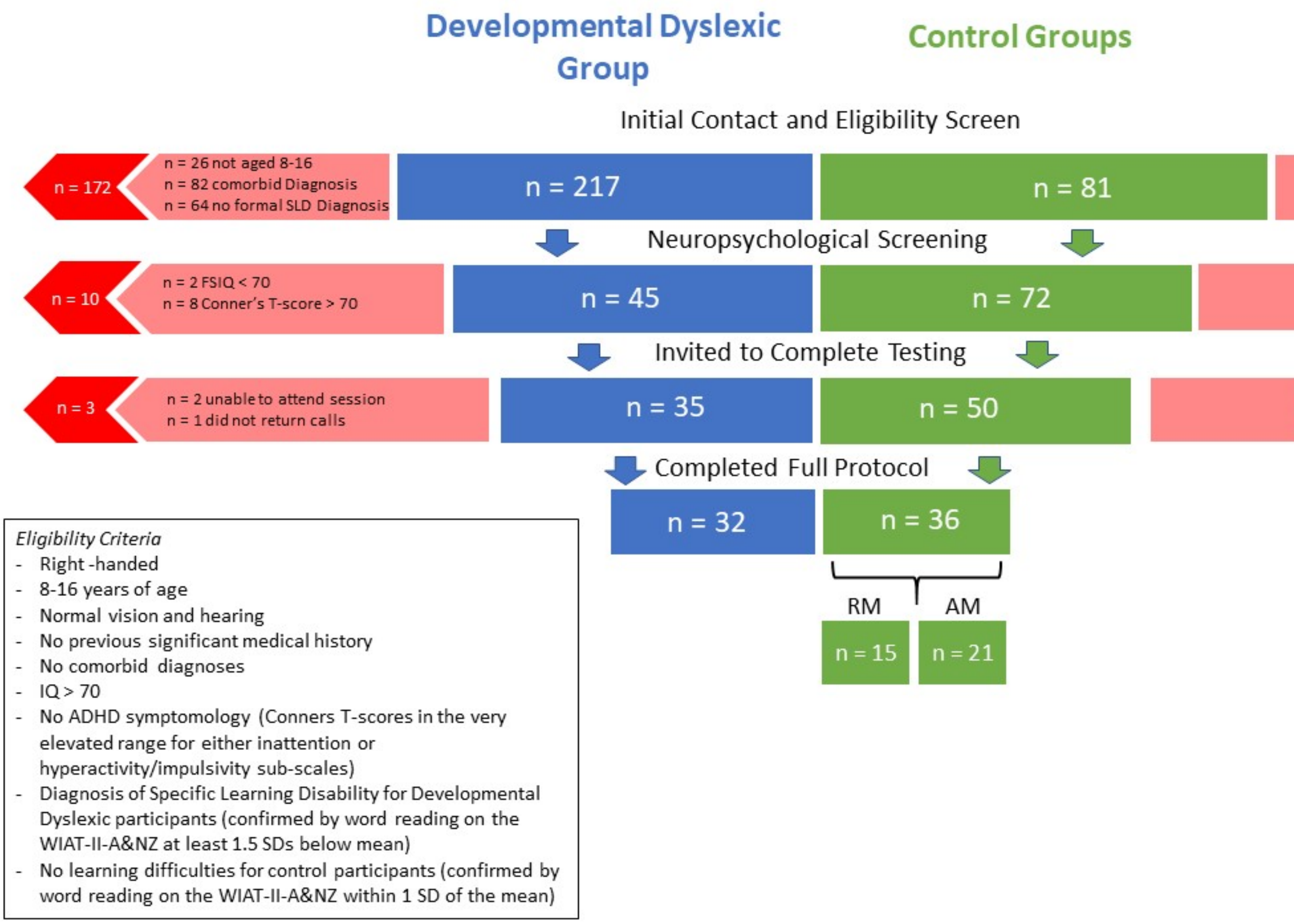


Figure 1. Flow of participant recruitment through protocol.

Note. ADHD = attention-deficit hyperactivity disorder. AM = age matched. IQ = intelligence quotient. RM
deviation. WIAT-II-A&NZ = Wechsler Individual Achievement Test - Second Edition, Australian and New Z

The final sample included 68 participants across the three groups; 32 in the DD group with dyslexia (16 females), 21 in the AM control group (11 females) and 15 in the RM control group (9 females; see Table 1 for participant characteristics).

Table 1. *Participant Characteristics.*

	Developmental Dyslexic (DD) Group	Age-matched (AM) Controls	Reading-matched (RM) Controls
	M (SD)	***M (SD)***	***M (SD)***
Age (years)	12.31 (1.45)	12.29 (1.51)	9.87 (0.77)
Hollingshead Socioeconomic Status Score	52.22 (12.67)	53.93 (12.43)	55.77 (13.54)
Intellectual Functioning (WISC-IV-SF)			
FSIQ	99.84 (15.71)	105.33 (16.42)	105.87 (16.79)
PRI	98.81 (15.70)	111.19 (14.61)	106.20 (14.51)
PSI	92.91 (11.52) [b]	102.29 (13.65)	105.93 (13.00)
WMI	92.22 (8.30) [a]	111.43 (14.16)	100.67 (14.25)
VCI	102.59 (13.51)	112.14 (10.96)	114.53 (8.40)
Word Reading Ability (WIAT-II-A&NZ)			
Word Reading Raw Score	88.22 (8.73)[a]	120.33 (4.55)	93.33 (9.26)
Word Reading Standard Score	70.78 (7.05) [a]	109.57 (6.84)	110.07 (10.04)
Word Reading Age Equivalent	8.19 (0.74) [a]	15.49 (2.45)	8.49 (0.74)
Reading Profile (CC2)			
Regular Word Reading	29.16 (7.65) [a, b]	48.67 (3.14)	32.40 (7.07)
Nonword Reading	13.97 (7.04) [a, b]	41.62 (4.28)	20.80 (8.55)
Irregular Word Reading	17.94 (4.75)[b]	30.86 (4.84)	13.60 (4.17)
Reading Profile Score	-0.07 (0.09) [a, b]	0.20 (0.10)	0.13 (0.15)
ADHD Symptoms (Conners 3 Sub-scales)			
Inattention *T*-Score	66.03 (13.30) [a,b]	51.43 (11.35)	53.80 (9.24)
Hyperactivity/Impulsivity *T*-Score	65.91 (13.46) [a,b]	55.33 (10.22)	57.87 (8.86)
Learning Problems *T*-Score	76.84 (10.03)[a,b]	50.19 (11.37)	50.53 (6.11)
Executive Functioning *T*-Score	63.75 (15.24) [a,b]	49.95 (9.69)	54.56 (7.68)
Aggression *T*-Score	57.16 (12.27)	48.57 (4.82)	53.20 (12.10)
Peer Relations *T*-Score	70.63 (12.27)	63.10 (10.99)	65.73 (11.02)

Note. ADHD = attention-deficit hyperactivity disorder. CC2 = Castles and Coltheart Test. FSIQ = Full-scale IQ score. PRI = Perceptual Reasoning Index. PSI = Processing Speed Index. VCI = Verbal Comprehension Index. WIAT-II-A&NZ = Wechsler Individual

Achievement Test - Second Edition, Australian and New Zealand Standardised Edition. WISC-IV-SF = Wechsler Intelligence Scale for Children - Fourth Edition, Short-Form. WMI = Working Memory Index.

[a] group difference between DD group and AM controls

[b] group difference between DD group and RM controls

Materials

Word reading ability.

The word reading subtest of the Wechsler Individual Achievement Test - Second Edition, Australian and New Zealand Standardised Edition (WIAT-II-A&NZ; Wechsler, 2005) measured word reading ability. Participants read aloud a list of words of increasing difficulty. A point was awarded for each correctly pronounced word, with the test discontinued after 7 consecutive errors (scores of 0). A total raw score (range 0-131) as well as an age standardised score (*M* = 100, *SD* = 15) were calculated for each participant.

Reading profile.

The Castles and Coltheart Test 2 (CC2) assessed lexical and sublexical abilities (Castles & Coltheart, 1993; Castles et al., 2009). The CC2 comprises 165 words, a list of 55 nonwords (e.g., nonsense words such as ‘gop’) that can only be successfully read through the sublexical pathway, a list of 55 irregular words (e.g., ‘yacht’) that can only be read via the lexical route, and a list of 55 regular words that can be read accurately by a combination of both routes. The regular and irregular words are matched on frequency, length and grammatical class. The nonwords also vary in their length and in the complexity of the grapheme-phoneme translations. Participants read words aloud one at a time randomly presented from lists which increased in difficulty. Discontinuation occurred for a list when 5 consecutive errors were made with the test completed when either the child completed or discontinued on all three lists. Responses were audio-recorded to allow for double scoring.

Reading profile score was calculated as the ratio of the total number of items accurately read from the nonword and irregular lists, divided by the total number of items in each list: (raw $score_{nonword}$-raw $score_{irregular}$)/55. Scores ranged from -1 to +1. Negative values reflected better irregular word readers (i.e., poorer relative sublexical skills), whereas positive values reflected better nonword readers (i.e., poorer relative lexical skills). Larger numbers indicated greater disparity between sublexical and lexical skills.

Perceptual decision making.

A bilateral version of a random dot-motion task was used to assess perceptual decision making (Britten, Shadlen, Newsome, & Movshon, 1992; Kelly & O'Connell, 2013; Loughnane et al., 2016; Newsome, Britten, & Movshon, 1989). Participants were required to fixate centrally on a 5 x 5 pixel square whilst monitoring two peripheral patches of randomly moving dots (one patch in each hemifield) for targets defined by instances of coherent motion in the downward direction (see Fig. 1 for a trial schematic). The circular dot patches were of 8 degrees in diameter with the centre of each patch situated 4 degrees below and 10 degrees to the left and right of the central fixation point. Stimuli were white and presented against a black background. During random motion, an average of 150 white dots (each dot 6 x 6 pixels) were placed at random and independent positions within each of the left and right hemifield circular patches at a rate of 21.25 frames per second. During coherent motion, the coherence threshold was set to 50% such that half of the dots were randomly selected on each frame to be displaced by a fixated distance of 0.282 degrees in a downward direction on the following frame, resulting in a motion speed of 6 degrees/second. As per Kelly and O'Connell (2013), coherent motion was introduced after a random delay via a seamless step transition from incoherent to coherent motion. Coherent motion was always in the downward direction and only ever occurred once per trial in either the left or right hemifield with equal probability. Whilst a target was displayed, random dot motion continued in the alternate patch. Inter-target intervals of random motion lasted either 3.06, 5.17 or 7.29 seconds, chosen randomly on a trial-by-trial basis.

On target detection, participants provided a speeded button press with their thumb. Response hand was counterbalanced across blocks such that for an entire block, participants responded to all targets regardless of presentation hemifield with one hand. Response hand was then switched for the following block. Both accuracy and reaction time were measured for all target conditions (right and left hemifield targets; right and left response hands). Feedback regarding accuracy and reaction time (responses either faster or slower than one second on average) was provided to the participants after each block.

The task was divided into 1 practice block followed by 12 discrete blocks. Each block comprised 18 target trials presented continuously. Accordingly, participants completed 216 trials in total. Each block lasted 2.5 minutes followed by a short break. The paradigm was run on a 32-bit windows XP machine using MATLAB (MathWorks) and the Psychophysics Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002; Pelli, 1997). Stimuli were presented using a 51cm CRT display (85Hz refresh rate; 1024 x 768 resolution).

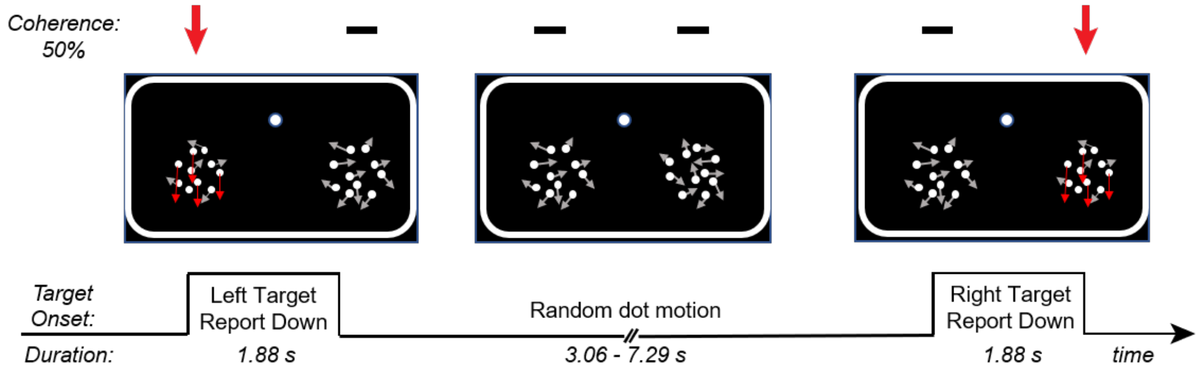


Figure 2. An example of a single target trial from the random dot-motion paradigm. Participants were required to fixate centrally on the white dot and peripherally monitor the continuously moving random dots. When participants perceived the target indicated by an instance of coherent downward motion (red arrows), they responded via single-handed mouse click.

ADHD symptoms.

The short form of the parent-rated Conners - Third Edition (Conners, 2008) assessed ADHD symptoms. Six sub-scales measuring inattention, hyperactivity/impulsivity, learning problems, executive functioning problems, defiance/aggression and peer relations were obtained with standardised *T*-scores based on normative data for age- and gender used (*M* = 50, *SD* = 10). Scores above 70 (+2 *SD*s above the mean) were considered 'very elevated'.

Intellectual functioning.

The short form of the Wechsler Intelligence Scale for Children - Fourth Edition (WISC-IV-SF; Weschler, 2003) was used to measure intellectual ability. Participants completed seven subtests (block design, similarities, vocabulary, matrix reasoning, digit span, coding and symbol search), summed to generate an age-standardised full-scale intelligence quotient and four index scores; verbal comprehension, perceptual reasoning, working memory and processing speed (*M* = 100, *SD* = 15).

Socioeconomic status.

The Hollingshead Four-Factor Index of Socioeconomic Status (Hollingshead, 1975) was used to estimate the socioeconomic status of a child's family based on four domains: marital status, employment, education and occupation. Scores were computed for each parent by summing their occupation score multiplied by 5, and their education score multiplied by 3, with scores ranging from 8 to 66 (higher scores indicated higher socioeconomic ranking). Scores for two-parent families were taken as the average and individual scores were used for single-parent families.

Procedure

Following screening, eligible participants attended a testing session to complete the experimental protocol. Parents completed written consent as well as a brief survey to gather demographic (e.g., date of birth, gender, handedness) and medical history (e.g., details of current diagnoses) information about their child. As this study was nested within a larger project examining visual attention in children with dyslexia using multiple assessment techniques, parents also completed a range of behavioural questionnaires about their child whilst children undertook various neuropsychological and cognitive paradigms including the random dot-motion task.

The random dot-motion task was carried out in a dimly lit sound-attenuated room with participants seated, supported by a chin rest, at 56cm viewing distance. Before beginning the task, the experimenter explained the task verbally and completed a demonstration trial. Participants were instructed to maintain central fixation during the task and to avoid blinking or moving during trials as much as possible. They were, however, encouraged to move and blink during the short breaks between trials if desired. Participants were then able to complete a practice trial with the examiner. When participants had mastered a practice trial, they were left alone in the room to complete test blocks. Continuous EEG data acquired from 65 scalp electrodes using a Brain Products BrainAmp DC system digitised at 500Hz was recorded throughout all test blocks.

This study was approved by the Monash University Human Research Ethics Committee (CF15/3184_2015001359) and the Victorian Department of Education and Training (2015_002847). In accordance with the Helsinki declaration, informed consent was provided by all parents and verbal assent from all participating children.

Data Processing

Performance measures from the random dot-motion task included accuracy (measured as the percentage of correctly identified targets), reaction time (measured as the average time taken to respond to targets in milliseconds) and false alarm rate (measured as the number of premature responses to targets).

EEG and behavioural data were processed using a combination of custom scripts and EEGLAB routines (Delorme & Makeig, 2004) implemented in MATLAB (MathWorks). The raw EEG data was first processed using the HAPPE protocol (Gabard-Durnam, Leal, Wilkinson, & Levin, 2018). A 1Hz High pass filter was first applied to the raw EEG data. Channels with significantly high average log power were rejected before an independent component analysis was applied to remove EEG artifacts such as eyeblinks and muscle movements. The rejected channels were then interpolated, and the EEG data was average re-

referenced. The processed EEG data was then filtered at 35Hz using 4th order Butterworth filters. EEG epochs were extracted using a window of -0.7 seconds to 1.5 seconds around target onset and baseline corrected relative to the 100ms interval ending at target onset. Trials were excluded from analysis if reaction times were < 300ms (pre-emptive responses) or > 2100ms (responses after coherent motion offset), and if the processed EEG amplitude from any channel exceeded $100\mu V$ from 100ms before the target onset to 100ms after the response.

The CPP was measured at peak electrode Pz (Kelly & O'Connell, 2013; Loughnane et al., 2016; Newman, et al., 2017; O'Connell et al., 2012; Twomey, Murphy, Kelly, & O'Connell, 2015). CPP build-up rate was defined as the slope of a straight line fitted to the response locked waveform from 150ms before to the time of the maximum CPP amplitude pre-response (Kelly & O'Connell, 2013; Loughnane et al., 2016; O'Connell et al., 2012). CPP onset latency was measured by performing running sample-point by sample-point *t* tests against zero across each participant's stimulus-locked CPP waveforms. CPP onset was defined as the first point at which the amplitude reached significance at the 0.05 level for 10 consecutive points (as described in the methodology of Foxe and Simpson, 2002).

N2 components were measured contralateral and ipsilateral to the target location at electrodes P7 and P8 (Loughnane et al., 2016). Amplitude and latency were defined as the magnitude and time of the most negative amplitude in the stimulus locked average waveform between 150 and 450ms for contralateral N2 and between 200 and 550ms for ipsilateral N2 (Loughnane et al., 2016).

Pre-target α power was calculated from the parietal regions of interest using the temporal spectral evolution method (ROIs; left hemisphere: PO7, PO3; right hemisphere: PO4 PO8; Newman et al., 2013; Thut, Nietzel, Brandt, & Pascual-Leone, 2006). EEG data from all channels were band pass filtered to the range of 6 to 11Hz before being rectified. A moving average window of 100ms with 50ms increments was then applied to the EEG data. Pre-target α power was defined as the mean power from 500ms before target onset to the target onset and aggregated to participant means. Pre-target α asymmetry was calculated as ($_{right}$ROI α − $_{left}$ROI α)/($_{right}$ROI + $_{left}$ROI α) as per Newman et al., (2017).

β power (15-25 Hz) and steady state visual evoked potentials (SSVEPs, first harmonic; 21.25Hz, second harmonic; 42.5Hz) were measured using short-time Fourier transform with a 200ms moving average window of 20ms step-size (O'Connell et al., 2012). β signal was measured from a standard motor site C3 whereas the SSVEP signals were measured from the standard site Oz (Dockree et al., 2017, O'Connell et al., 2012). β and SSVEP waveforms were baselined with respect to 100ms to 0ms before target onset. β and SSVEP amplitudes were defined as the mean amplitude of the response locked waveform from 100ms before to 100ms after the response whereas the build-up rate of β was defined as the slope of a straight line fitted to the response locked waveform from 100ms before response to the time of the response (Newman et al., 2017).

Statistical Analyses

Group comparisons were first conducted to examine whether the DD group performed differently to either the AM or RM control groups in terms of accuracy, false alarm rate, reaction time and EEG components, and whether differences were seen across target hemifield as well as response hand. A series of three-way mixed model ANOVAs were conducted with performance measures (accuracy, reaction time and false alarm rate) and the five event-related potential components (SSVEPs, Pre-target α, N2, CPP and β) as the dependent variable to examine the effect of group (DD group, AM and RM controls), target hemifield (left and right), response hand (left and right) as well as their interactions. For EEG measures, alpha was set to 0.008 corresponding to a Bonferroni correction for the 5 components. In instances where a main effect of group was identified, planned contrasts tested differences between the DD group and AM controls, and the DD group and RM controls respectively. Simple main effects were conducted to follow-up any significant interactions. Effect sizes in terms of eta squared are provided for all main analyses.

Moderation analyses were performed to examine ERP components for which the DD group differed from controls to determine whether differences were driven by participants with a specific reading profile (relatively poorer lexical or sublexical skills). Simple slopes analyses were conducted to determine at which reading profile score (taken at the mean and at 1 standard deviation above and below the mean) the relationship between word reading ability and the respective component became statistically significant (Hayes, 2013). All analyses were run in IBM SPSS Statistics Version 25. The PROCESS macro was used for moderation analyses (Hayes, 2013) with the HC3 (Davidson-MacKinnon) heteroscedasticity-consistent inference applied.

Data Availability

No part of the study analysis plan was pre-registered prior to the research being conducted. The conditions of ethics approval did not permit public archiving of anonymised study data. Readers seeking access to the data should contact the lead author or the local ethics committee at Monash University. Access can be granted only to named individuals in accordance with ethical procedures governing the reuse of clinical data.

Results

Group Comparisons

Performance measures.

There were no significant main effects of group on measures of accuracy or false alarm rate. There was a main effect of group for reaction time, $F(2,65) = 6.74$, $p = .002$, $\eta^2 = .172$. The DD group responded significantly more slowly to targets than both the AM controls, $t(51)$, $= -3.05$, $p = .004$, 95% CI [-157.73, -32.53], and RM controls, $t(45)$, $= -2.87$, $p = .006$, 95% CI [-149.56, -26.26]. There was also an interaction for reaction time between target hemifield and response hand, $F(1,65) = 8.18$, $p = .006$, $\eta^2 = .112$. Follow up analyses revealed that all participants responded slower to targets presented in the right hemifield with their left compared with their right hand, $t(67) = 2.09$, $p = .040$, 95% CI [0.47, 20.11]. There were no differences between response hands for left hemifield targets.

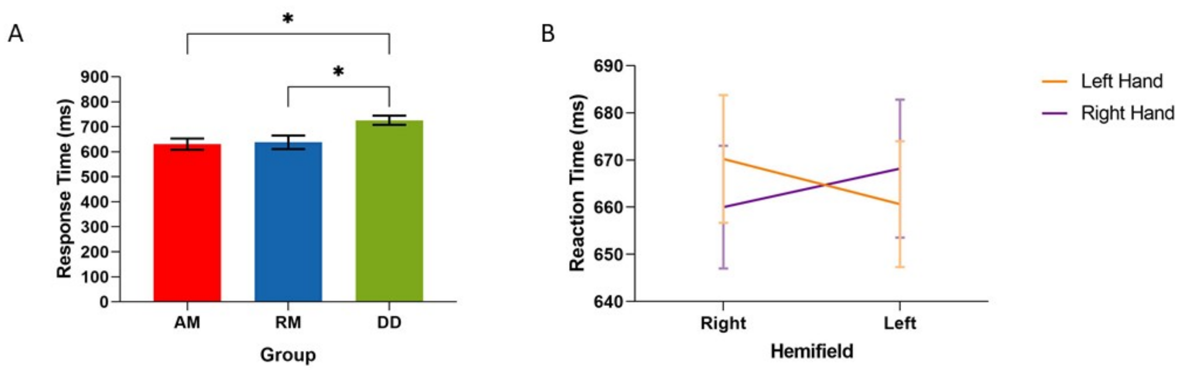


Figure 3. **A**. Mean reaction time across groups showing slower response times for DD participants (shown in green) compared with both AM controls (shown in red) and RM controls (shown in blue). The DD group performed 95.13ms slower on average than AM controls and 87.91ms slower than RM controls. **B**. Reaction time is shown across hemifield and response hand for all participants. All participants responded 10.29ms faster on average to targets presented in the right hemifield with their right hand reflecting a spatial compatibility effect. Comparable stimulus-response compatibility effects were seen for the left hand as a function of target hemifield, albeit non-significant. *Note.* Error bars represent standard error of the mean.

Event-related Potential Components.

SSVEPs.

No significant main effects or interactions were seen for slope or amplitude within the first SSVEP harmonic. There was a main effect of group for slope, $F(2,65) = 3.48$, $p = .037$, $\eta^2 = .097$, and amplitude, $F(2,65) = 3.48$, $p = .037$, $\eta^2 = .097$ in the second SSVEP harmonic however this did not survive corrections for multiple comparison (see Supplementary Fig. 1 for scalp topographies and waveforms).

Pre-target α.

There was a main effect of group for pre-target α power, $F(2,65) = 3.62$, $p = .032$, $\eta^2 = .100$, however, this was not statistically significant following corrections for multiple comparisons. There was also an interaction of hemifield by response hand by group, $F(2,65) = 3.35$, $p = .041$, $\eta^2 = .093$, however, again this did not survive correction for multiple comparisons. No significant main effects or interactions were identified for pre-target α asymmetry.

N2.

No significant group differences were seen for either the contralateral or ipsilateral N2 amplitudes or peak latencies. There was a main effect of response hand for contralateral N2 latency, $F(1,67) = 4.63$, $p = .035$, $\eta^2 = .067$, however this did not survive multiple comparison corrections (see Supplementary Fig. 3 for scalp topographies and waveforms).

CPP.

There was a main effect of group for response locked CPP slope, $F(2,65) = 5.70$, $p = .005$, $\eta^2 = .149$, amplitude, $F(2,65) = 5.46$, $p = .006$, $\eta^2 = .144$, peak latency, $F(2,65) = 5.94$, $p = .004$, $\eta^2 = .155$, but not onset, $F(2,65) = 0.86$, $p = .431$, $\eta^2 = .050$. Results indicated that the DD group demonstrated significantly shallower CPP slopes compared with both the AM controls, $t(51) = 3.00$, $p = .004$, 95% CI [0.004, 0.02], and RM controls, $t(45) = 3.04$, $p = .050$, 95% CI [0.003, 0.02]. The amplitude of the CPP was reduced in the DD group compared with both the AM controls, $t(51) = 2.80$, $p = .007$, 95% CI [1.03, 6.29], and the RM controls, $t(45) = 2.86$, $p = .006$, 95% CI [1.11, 6.34]. The peak latency of the CPP occurred earlier in the DD group compared with both the AM controls, $t(51) = 3.37$, $p = .001$, 95% CI [5.58, 22.07] and the RM controls, $t(45) = 1.88$, $p = .050$, 95% CI [-0.13, 16.01]. Thus, performance of the DD group was characterised by an earlier latency, a shallower slope of evidence accumulation and a reduced amplitude of the CPP compared with both AM and RM control groups.

There was a significant main effect of response hand for CPP amplitude, $F(1,67) = 9.17$, $p = .004$, $\eta^2 = .124$, whereby amplitudes were higher for targets that were responded to with the right compared with left hand, $t(67) = 3.32$, $p = .001$, 95% CI [0.60, 2.42]. Although no main effects were seen for CPP onset, there was a significant interaction between group and response hand, $F(2,65) = 7.40$, $p = .002$, $\eta^2 = .309$. Follow up analyses revealed an earlier CPP onset for left-handed responses to targets in the AM group, $t(14) = 3.46$, $p = .004$, 95% CI [29.60, 125.87], whereas no differences were seen across response hands for either the DD or RM groups.

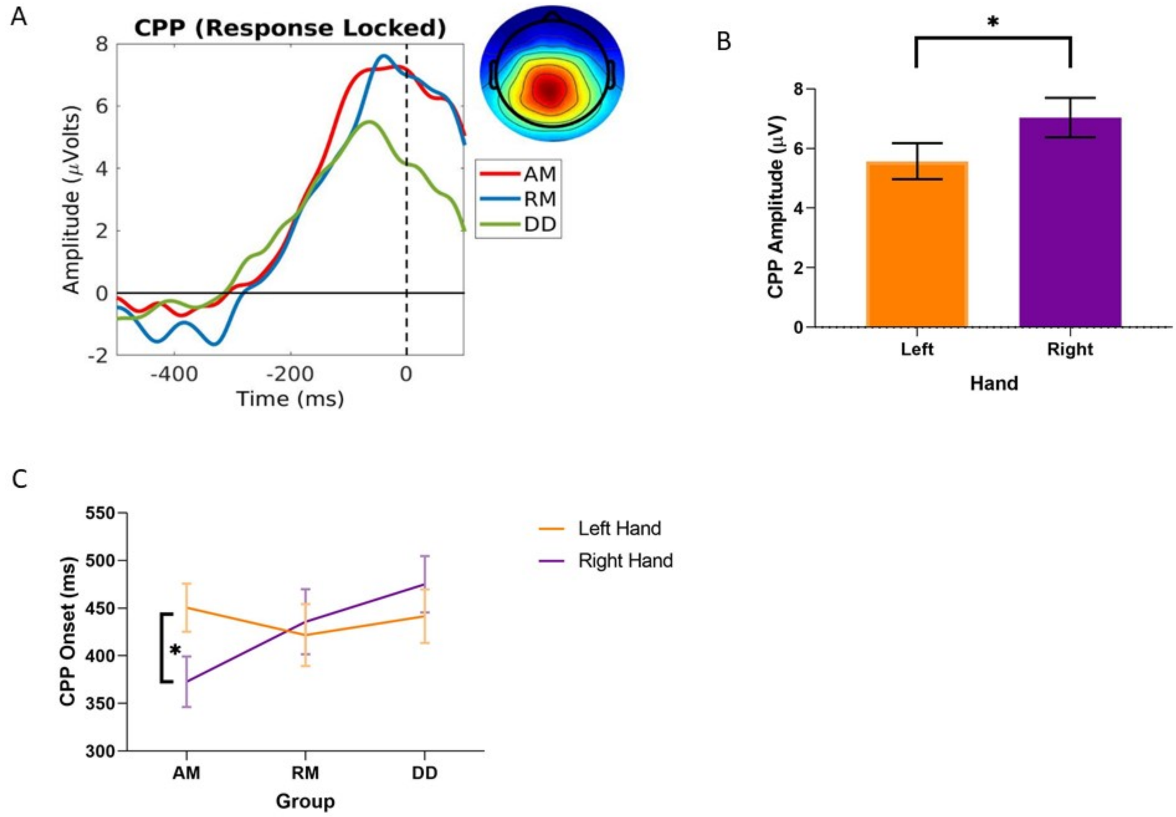


Figure 4. **A.** Scalp topography and CPP waveforms across groups. The DD group (shown in green) demonstrated reduced CPP slope by 0.012μV/ms compared with both AM and RM control groups (shown in red and blue respectively). CPP amplitude was also 3.66μV lower compared with the AM controls, and 3.72μV lower compared with the RM controls. CPP peak latency occurred 13.83ms earlier compared with the AM controls and 7.94ms earlier compared with RM controls. **B.** Mean CPP amplitude shown across hand for all participants indicating higher amplitudes (1.51μV on average) for targets in which participants responded with their right hand compared with their left hand. **C.** Mean CPP onset is also shown across both response hand and groups with a significant difference only evident in the AM group; CPP onset was 77.73ms earlier on average for right compared with left-handed responses.

β.

No significant group differences were seen for contralateral *β* slope or amplitude (see Supplementary Fig. 4 for scalp topographies and waveforms). There was, however, a main effect of hand for both slope, $F(1,67) = 5.83$, $p = .019$, $\eta^2 = .082$, and amplitude, $F(1,67) = 11.35$, $p = .001$, $\eta^2 = .149$, the latter surviving multiple comparison correction. *β* amplitude was higher for left-handed responses compared with right-handed responses across all participants, $t(67)$, $p = .001$, 95% CI [-0.30, -0.08].

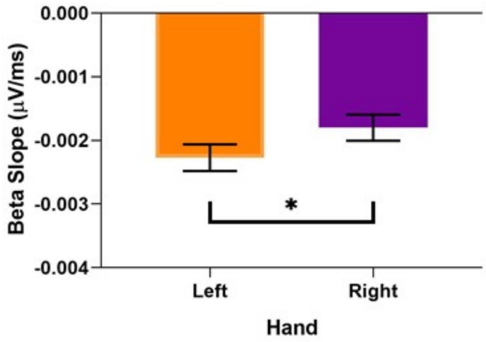


Figure 5. Mean β slope indicating β was 0.0005µV/ms steeper and amplitude was 0.19µV greater on average for left-handed responses compared with right. *Note.* Error bars represent standard error of the mean.

Moderation Analyses

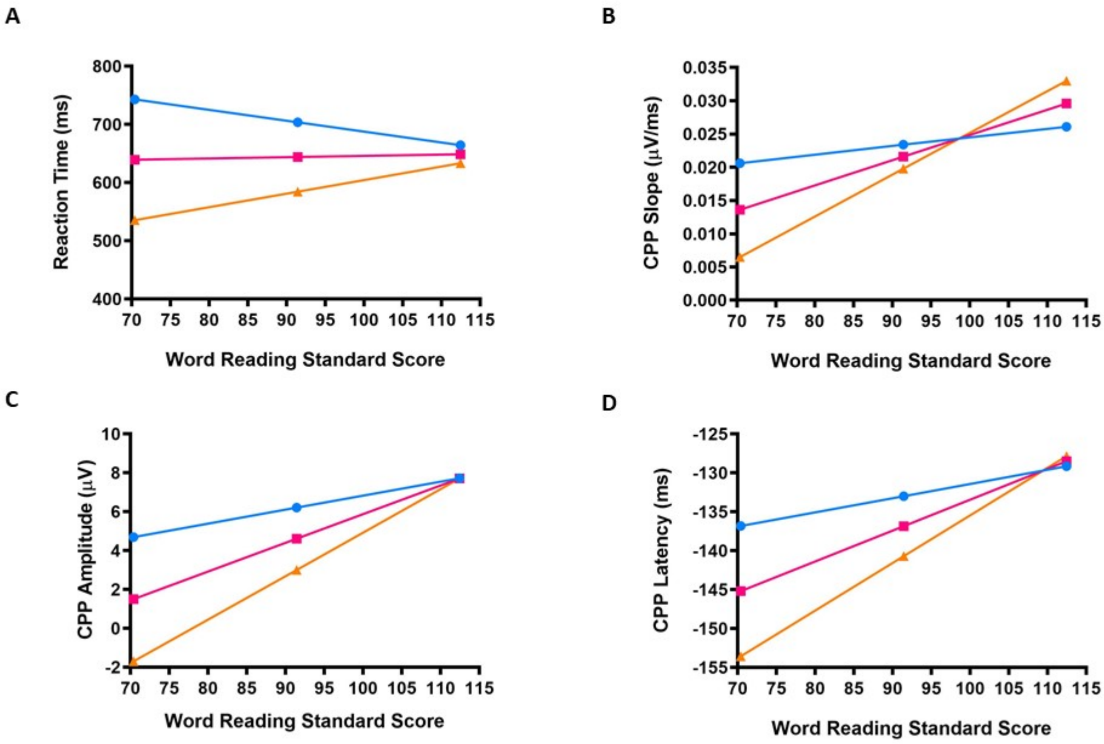
Given significant group differences for reaction time and CPP components, analyses were conducted to assess whether reading profile moderated the relationship between word reading ability and reaction time as well as CPP slope, amplitude and latency in children with dyslexia and age matched controls (see Table 2 for a summary of the results). All overall models were significant indicating that word reading ability and reading profile together predicted reaction time and CPP components. The interaction between word reading ability and reading profile was also significant. This indicated that the relationship between word reading ability and the outcome variables (reaction time and CPP components) differed for participants across the spectrum of reading profiles. Simple slopes analyses revealed that the relationship between word reading ability and all three CPP components was significant for those with a specific reading profile indicative of equivalent or poorer relative lexical skills but not for those with relatively poorer phonological skills. For reaction time, the relationship was significant only for those with relatively poorer lexical skills. Thus, reaction time was slower, the evidence accumulation process had a shallower build-up rate (slope) and reached a lower peak amplitude earlier in children with DD with reading profiles characterised by poorer relative lexical abilities (i.e., lexical DD).

:able 2. *Summary of Regression Models for the Word Reading Ability, Reaction Time and CPP components as Mod*

Model		***b* [95% CI]**
2	Constant	707.86
Reaction Time		[529.42, 886.29]
$F(3,64) = 9.09$, $p < .001$, $R^2 = .279$	Word Reading Ability	-0.048
		[-2.54, 1.59]
	Reading Profile	-1529.57
		[-2565.66, -493.49]
	Word Reading Ability x Reading Profile	12.77
		[2.53, 23.00]
2	Constant	-0.01
CPP Slope		[-0.03, 0.020]
$F(3,64) = 4.41$, $p = .001$, $R^2 = .188$	Word Reading Ability	0.001
		[0.001, 0.002]
	Reading Profile	-0.15
		[-0.29, -0.01]
	Word Reading Ability x Reading Profile	0.002
		[0.001, 0.03]
3	Constant	-6.03

CPP Amplitude		[-11.91, -0.14]
$F(3,64) = 7.31$, $p < .001$, $R^2 = .217$	Word Reading Ability	0.12
		[0.05, 0.19]
	Reading Profile	-51.87
		[-91.89, -11.84]
	Word Reading Ability x Reading Profile	0.46
		[0.05, 0.87]
4	Constant	-165.26
CPP Latency		[-186.25, -144.27]
$F(3,64) = 4.52$, $p = .006$, $R^2 = .168$	Word Reading Ability	0.33
		[0.08, 0.57]
	Reading Profile	-142.52
		[-261.62, -23.41]
	Word Reading Ability x Reading Profile	1.30
		[0.08, 2.53]

Vote. *b* = unstandardised regression coefficient. *SE* = standard error. *B* = standardised regression coefficient. R^2 = R-



'igure 6. The relationship between word reading ability (Word Reading Standard Score) and Reaction Time (**A**), C
atency (**D**) as moderated by reading profile (Profile Score). Accordingly, children with DD (Word Reading Stanc
quivalent or relatively poorer lexical compared with sublexical reading skills specifically demonstrated slower reac
mplitudes and earlier CPP latencies. *Note.* Reading profile was estimated at three points corresponding to 1 stand
vell as at the mean in all moderation analyses. This corresponded to a reading profile score of -0.11 (poorer lexical r
eading skills) indicating a discrepancy of 6 and 12 words respectively, as well as at 0 indicating equivalent accuracy

Discussion

A wide array of visual deficits, particularly in motion processing, have been reported in the dyslexia literature (Laycock, Crewther, & Crewther, 2008; Schulte-Körne & Bruder, 2010). However, studies have predominantly focused on early detection of visual material (see Schulte-Körne & Bruder, 2010 for a review). With evidence that improvements in reading following intervention are not necessarily associated with corresponding changes in visual detection thresholds (Joo, Donnelly, & Yeatman, 2017), there has been an increasing move towards examining perceptual decision making beyond early sensory registration. Here, we show for the first time that slowed perceptual decision making in response to motion stimuli is a fundamental deficit in dyslexia, most prominent in those with relatively poorer lexical abilities. We extend this by identifying a specific slowing of the rate of evidence accumulation and an attenuation in the amplitude of decision thresholds, measured using EEG, as the neural correlate of this deficit.

The finding that overall, children with dyslexia are slower to respond to motion material adds to a substantial literature linking slowed visual processing and poor reading ability. Most commonly, this has been associated with slowed naming (Fawcett & Nicolson, 1994; Nicolson, 2007), but it also aligns with evidence that other cognitive deficits, such as reduced visual attention span are underpinned by reduced processing speed (Bogon, Finke, & Stenneken, 2014; Dubois et al., 2010; Stefanac et al., 2019; Stenneken et al., 2011). Importantly, slowed perceptual processing in this study was independent of reduced reading ability in that it was present in children with dyslexia but not those with equally immature reading systems (i.e., reading matched controls). This provides evidence that slowed perceptual decision making is fundamental to dyslexia and not a result of reduced exposure to text.

When viewing single words, accomplished readers automatically match visual material to that stored in the mental lexicon, a process that is essential when reading words via a fluent, whole-word, lexical approach (Heyman, Rensbergen, Storms, Hutchison, & Deyne, 2014; Lobier, Dubois, & Valdois, 2013). Without this automation, readers must allocate greater cognitive resources towards decoding via the sublexical route resulting in inaccurate conversion of irregular words, slowing down the reading process and reducing availability of resources for comprehension (LaBerge & Samuels, 1974). The notion that reduced processing of visual material bears a substantial impact on rapid lexical access may explain why our results indicate slowed perceptual processing was most prominent in children whose poor reading was specifically characterised by relatively poorer lexical abilities. Seemingly, these children are unable to take in sufficient visual material which, in the context of reading, inhibits adequate retrieval of corresponding output from the lexicon. Therefore, these children must rely more heavily on engaging sublexical approaches to reading which are unsuccessful when irregular words are presented, hence their poorer relative lexical skills. This in keeping with evidence suggesting that children with dyslexia who do not display characteristic phonological deficits instead present with slow naming abilities and reduced visual attention span, which likely reflects an inability to take in visual material efficiently to facilitate whole-word reading as shown here (Catts, Gillispie, Leonard, Kail, & Miller, 2002; Hanley & Gard, 1995; Valdois et al., 2003). Although, it is important to note that there is some evidence that motion detection abilities are associated with phonological deficits in dyslexia (Borsting et al., 1996; Spinelli et al., 1997), this is not always the case (Ridder et al., 2001). Moreover, motion processing beyond sensory detection is more commonly associated with reading fluency and speed (Demb, Boynton, Best, & Heeger, 1998) and thus may be more closely tied to reading via the lexical route as shown here. From a clinical perspective, some individuals with dyslexia are responsive to remediation targeting reading accuracy however efforts to improve fluency or automaticity in reading is generally unsuccessful (Norton & Wolf, 2012; Wolf & Bowers, 2000). Therefore, further research and clinical efforts are required to identify how best to improve reading fluency, which may be more relevant to this specific subgroup of children with dyslexia.

It is important to understand the relevance of the current results in the context of what we know about visual motion processing. Of the two major visual pathways (Livingstone & Hubel, 1988), the one sensitive to motion perception is derived from magnocellular subdivisions of the lateral geniculate nucleus which receive information from M-type ganglion cells from the retina, projecting into the occipital lobe where information is processed in a hierarchical fashion from V1 to V5/MT (Callaway, 2005). M-type cells are responsive to low contrast stimuli presented at high temporal and low spatial frequencies (Kaplan & Shapley, 1982). Thus, previous evidence that individuals with dyslexia perform poorly on tasks requiring magnocellular input (i.e., reduced sensitivity to motion stimuli and greater contrast detection thresholds; Livingstone et al., 1991), was initially thought to reflect dysfunction in these cells (Stein, 2001). However, despite the appealing simplicity of this account, there is inconsistent evidence of reduced magnocellular sensitivity (see Skottun, 2000 and Stein, Talcott, & Walsh, 2000 for a comprehensive debate regarding the evidence both for an against the magnocellular hypothesis in dyslexia). Researchers have subsequently emphasised the important role of secondary feedback loops from V5 to V1 for motion perception (Bullier, 2001; Silvanto, Lavie, & Walsh, 2005; Stein, 2014, 2018) and drawn links between this mechanism and reading ability (Laycock & Crewther, 2008). In typically reading individuals, the magnocellular system processes motion information rapidly via dorsal networks and then retroinjects this back from V5 into V1 via feedback loops in time to be combined with ventrally processed parvocellular input arriving later. This feedback signal is thought to be largely driven by attentional mechanisms in the parietal lobe and initiated by frontal brain regions (Bar et al., 2006; Kveraga, Boshyan, & Bar, 2007) reflecting the frontoparietal attentional mechanisms described by Corbetta & Shulman (2002). During reading, magnocellular feedback is thought to suppress incoming parvocellular information to prevent saccadic activity elicited during one fixation from lingering after the initiation of the next fixation during reading. In dyslexia however, it is thought that the suppressive effect of the magnocellular system is diminished or absent, resulting in dysfunctional movement of binocular saccades across text that causes a mismatch of visual and auditory information (Livingston et al., 1991; Stein & Walsh, 1997). In fact, there is substantial evidence that the gap between processing visual and auditory information is larger in those with dyslexia pointing to a disproportionate asynchrony that impairs accurate binding of visual and verbal material to facilitate reading (Breznitz & Meyler, 2003; Breznitz & Misra, 2003).

Given the role of the parietal lobe in driving attentional feedback signals, recent research has sought to better understand the link between magnocellular feedback loops required for motion processing and reading. For instance, Laycock and colleagues (2009) demonstrated that disruption to these early feed-forward-feedback loops using transcranial magnetic stimulation in healthy individuals resulted in reduced accuracy of single word reading, adding to pre-existing evidence of dorsal, as opposed to ventral, contributions to reading (Chase, Ashourzadeh, Kelly, Monfette, & Kinsey, 2003; Kinsey, Rose, Hansen, Richardson, & Stein, 2004; Omtzigt, Hendriks, & Kolk, 2002). Our results might offer further clarity by revealing that slowing of visual motion processing in children with developmental reading difficulties is related to inefficient accumulation of visual evidence which has a neural basis in the parietal lobe, thus providing a developmental analogue of these findings. However, it should be noted that, that the relationship between visual motion processing and word reading does not appear to be significant unless it is under conditions requiring cognitively demanding processing (Braet & Humphreys, 2006). As Vidyasagar and Pammer (1999) argue, the inability of the magnocellular system to inhibit the parvocellular system is only evident when attentional demands are overextended and thus cannot provide the rapid input required for efficient inhibitory signaling. This might explain differences seen within the second harmonic of the SSVEP in the current study which, despite not surviving multiple comparison corrections, may reflect inefficient magnocellular functioning and a recruitment of attentional resources impacting on subsequent accumulation of sensory evidence (Fries, Reynolds, Rorie, & Desimone, 2001; Norcia, Appelbaum, Ales, Cottereau, & Rossion, 2015; Pammer, 2014).

Interestingly, despite the link drawn between motion processing and parietal lobe functioning via the magnocellular system, there was no evidence of any differences in performance or electrophysiology measured as a function of hemifield for any group. This is somewhat surprising given previous evidence of lateralized spatial attention deficits in dyslexia (Facoetti & Molteni, 2001; Facoetti, Paganoni, & Lorusso, 2000; Franceschini et al., 2012) and the important role that the parietal role plays in visuospatial attention (Maurizio Corbetta & Shulman, 2002). One notable difference here is that previous results demonstrating visuospatial dysfunction in dyslexia used spatial cuing paradigms with predictive cues (Facoetti et al., 2003) which activated endogenous, rather than exogenous mechanisms of attention whereby the participant pre-empted the following target. Further, visuospatial differences have been shown to be largely related to nonword reading (Facoetti et al., 2006) and thus may be less relevant to slowed visual motion processing associated with lexical reading here. Motion processing and magnocellular functioning also appear to be specific to temporal, as opposed to spatial, aspects of visual processing in reading (Solan et al., 2004). For example, a distinction between visuospatial and temporal deficits has been drawn using motion stimuli in dyslexia. Results indicated that although only mild impairments are evident on dot tasks assessing spatial processing, children with dyslexia perform significantly worse than typical readers on temporal dot tasks (Eden, Stein, Wood, & Wood, 1995). This suggests that speed deficits in dyslexia may be more pronounced than visuospatial deficits when using motion stimuli.

With respect to evidence accumulation specifically, sequential sampling models of perceptual decision making theorise that sensory information is repeatedly sampled and accumulated across time until which point the evidence reaches an action-triggering threshold (Ratcliff & Smith, 2004). This process of evidence accumulation depends not only on the strength of externally presented sensory evidence (stimulus intensity), but also on 'internal' sources of variability that affect an individual's capacity to adequately sample visual information (Kelly & O'Connell, 2013). For motion processing in particular, an individual must rapidly integrate both spatial and temporal information to accurately identify the presence of motion (Burr & Thompson, 2011). This is believed to occur in higher-order visual areas of the motion processing hierarchy, such as in MT/V5 (Born & Tootell, 1992; Britten et al., 1992). Thus, our finding of inefficient evidence accumulation in dyslexia may reflect poor integration of information in dyslexia affecting an individual's ability to effectively accrue evidence to make a decision. This is supported by findings showing that poorer motion sensitivity in dyslexia is predominantly observed using tasks that require either rapid sequential processing (Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001; Raymond & Sorensen, 1998) or prior adaptation to a stimulus (Johnston, Pitchford, Roach, & Ledgeway, 2016). In fact, both children and adults with dyslexia perform comparably to same-age controls when presented with stimuli using fewer frames (Raymond & Sorensen, 1998) with poor performance only evident following additional frames (Hill & Raymond, 2002). However, motion coherence tasks such as the one used here are not pure tests of motion detection. In motion detection tasks, targets are usually comprised of either on/off motion (i.e., all dots move randomly until the onset of the target whereby they begin to move together in a coherent fashion). Following onset of the target, all dots are 'signal' and therefore the optimal strategy is to integrate the information and average as many dots as possible. In motion coherence tasks such as ours however, 'signal' dots are interspersed with 'noise' dots and the relative proportion of signal to noise is reflected in coherence levels. Noise exclusion is therefore necessary to form a perceptual filter and isolate the signal dots to detect motion (Dakin, Mareschal, & Bex, 2005). Both integration and segregation have been previously recognized as competing visual forces (Braddick, 1993; Watamaniuk, Flinn, & Stohr, 2003) and have been proposed to have distinct neural mechanisms (McDonald, Clifford, Solomon, Chen, & Solomon, 2013). Thus, it may not be the integration of motion information that is dysfunctional in dyslexia but rather an inability to segregate noise from signal information. In support, there is evidence that individuals with dyslexia only show deficits processing visual material under high noise conditions. For instance, Sperling and colleagues (2005) demonstrate that children with dyslexia have elevated contrast thresholds when stimuli are presented in high noise, but this effect dissipates when stimuli are displayed without noise. Conlon and colleagues (2013) present further evidence that poor global motion sensitivity in adults with dyslexia is related to difficulties directing attention toward relevant information which is more evident when complex computational processing is required to detect motion. Talcott and colleagues (2000) also demonstrate that while those with dyslexia present with less sensitivity to coherent motion than controls at baseline, increasing coherent motion duration does not improve performance but increasing dot density does, suggesting that motion detectors have lower signal to noise ratios in dyslexia.

Both integrative and noise exclusion hypotheses for inefficient sampling of visual information in dyslexia could potentially arise due to increased neural noise. Broadly, neural noise refers to sources of random variability in single neurons which disrupt the balance of feedforward and feedback excitability and inhibitory activity within a neural network (Destexhe & Rudolph-Lilith, 2012). Although most noise occurs below a voltage threshold required for a corresponding action potential to occur, it may, in the case of dyslexia, be substantial enough to instigate an action potential disrupting cohesive signalling required to accrue a consistent response in favour of the decision. The notion that individuals with dyslexia may suffer from increased neural noise was initially proposed by Hancock, Pugh, & Hoeft (2017). They proposed that multifactorial sources of neural noise (possibly due to neural hyperexcitability within glutamatergic networks and disrupted neural migration related to genetic risk factors) disrupts the multi-modal binding of both visual and auditory material required for reading. In our case, increased intraindividual neural noise in the dyslexic group may lead to imprecision in estimating individual dot directions, which, when pooled or separated from noise signals, could lead to slower detection of coherent motion. This might disrupt the necessary interplay of both excitatory and inhibitory signalling in visual processing networks. The neural noise hypothesis may also explain parallel findings in the auditory domain which indicate weaker phoneme boundaries and suboptimal perceptual templates in children with dyslexia (Renvall & Hari, 2006). However, the specificity of the link between increased neural noise and poor reading is contentious as similar explanations have also been proposed for other neurodevelopmental disorders such as autism spectrum disorders (Simmons et al., 2007) and psychiatric conditions such as schizophrenia (Winterer et al., 2006). In addition, visual impairments associated with magnocellular dysfunction are also evident in both neurodevelopmental and psychiatric disorders (see Laycock, Crewther, & Crewther, 2007 for a review) suggesting that although inefficient visual processing is fundamental to dyslexia as shown here, it may represent a shared cognitive vulnerability that is also evidence across a diverse range of neuropsychological disorders.

Although integrative and noise exclusion hypotheses present as promising explanations for the CPP results shown here, they remain speculative and require validation with tasks specifically designed to probe internal noise (i.e., using equivalent noise analyses as described by Manning, Dakin, Tibber, & Pellicano, 2014 and Tibber, Kelly, Jansari, Dakin, & Shepherd, 2014) and across task conditions varying both the spatial and temporal frequency of the signal-to-noise ratio. For example, it would be worthwhile investigating whether increasing dot-density to boost the signal-to-noise ratio (as demonstrated by Talcott et al., 2000) impacts the ability of individuals with dyslexia to accumulate evidence indexed by the CPP. Utilising a two-alternative forced choice paradigm would also permit the use of computational techniques such as drift-diffusion modelling to link electrophysiology to the previously demonstrated behavioural evidence of suboptimal decision making in dyslexia (O'Brien et al., 2019). It would also be valuable to ascertain whether increasing task demands (i.e., requiring individuals to identify both the presence and the direction of coherent motion for instance) would have an effect on how evidence is accumulated. This would be particularly useful given accuracy was at ceiling in our study for all three groups. Increasing task difficulty may reveal more nuanced speed-accuracy trade-offs that impact perceptual decision making in dyslexia. Our results also require replication in larger samples to increase the power of identifying subtle differences that did not meet statistical thresholds with our sample (e.g., SSVEP results). It is important to note that the strict screening criteria utilised here was essential to obtain a relatively 'pure' sample of children with dyslexia and while we acknowledge that obtaining larger samples in this way adds to the recruitment burden, we encourage future researchers to use similarly stringent criteria, especially considering high comorbidities between reading difficulties and other neurodevelopmental disorders such as ADHD that might skew results (Willcutt & Pennington, 2000). There is also merit in considering how evidence accumulation may change across various stages of development in children with dyslexia using longitudinal approaches given evidence that aspects of decision making (i.e., the CPP in particular) and motion processing typically mature at different stages in typical development (Bogfjellmo, Bex, & Falkenberg, 2014; Braddick et al., 2016; Manning et al., 2019). We also acknowledge that matching participants on a single measure of reading ability fails to consider the range of reading skills (e.g., reading speed, fluency and spelling) that might be related to visual processing, particularly given the evidence of the link between reading fluency specifically and the dorsal visual pathway (Robin Laycock & Crewther, 2008).

To our knowledge, this is the first study to demonstrate a fundamental slowing in perceptual decision making in dyslexia linked to inefficient evidence accumulation at the neural level. It is also the first to assess perceptual decision making in response to motion processing whilst taking into account reading ability and the significant heterogeneity seen in developmental dyslexic samples. As such, the findings are novel in that they demonstrate dysfunctional evidence accumulation is central to dyslexia and not simply associated with immature reading ability. The results also show that this effect varied across individuals based on their reading profile. Together, these findings provide an impetus for the use of electrophysiological markers such as the CPP as objective clinical markers for the dyslexia and as a potential marker for treatment effectiveness. Since as many as 30% of school children with DD do not present with traditional phonological deficits (Whiteley, Smith, & Connors, 2007) and are therefore unlikely to respond successfully to phonological-based remediation (Wolf, 1997), the CPP may be a useful indicator for clinicians to identify children who are more likely to present with slowed decision making (i.e., lexical dyslexia) and targeted interventions may then be developed specifically for this group.

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Competing Interests

The authors report no competing interests.

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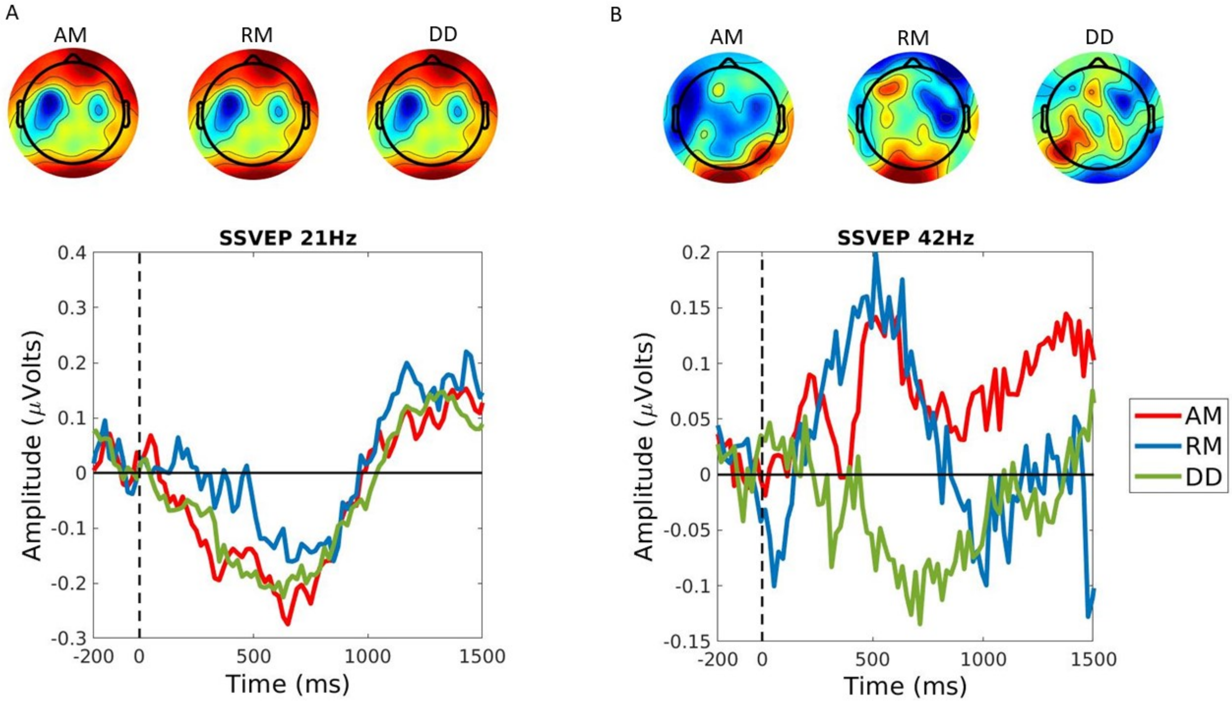
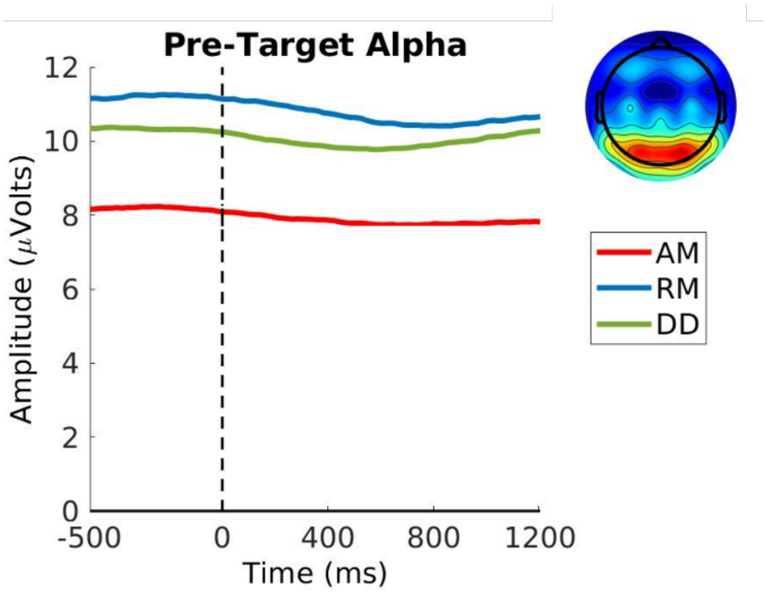
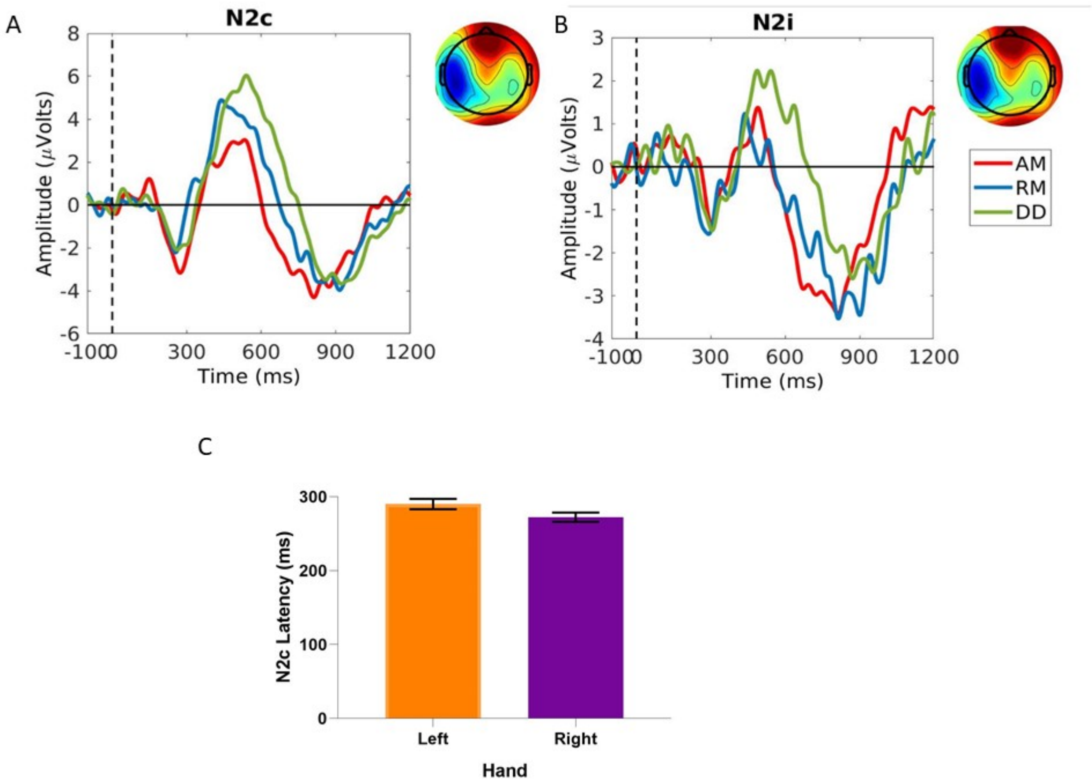
Supplementary Material



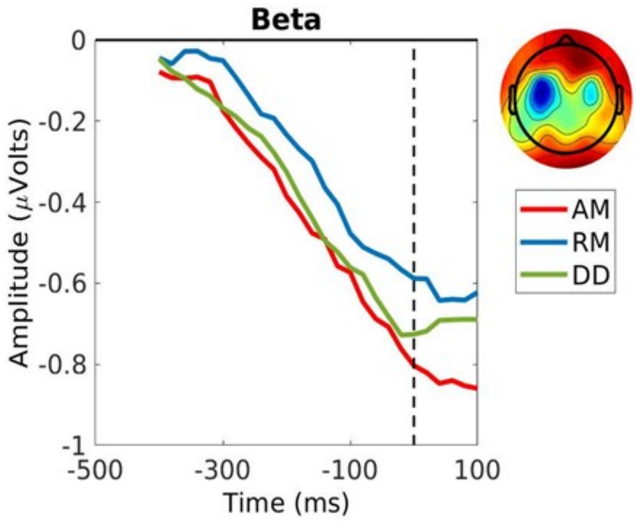
Supplementary Figure 1. Scalp topographies and waveforms for SSVEPs within the first (21Hz; **A**) and second harmonic (42Hz; **B**) across groups. No group differences were evident within the first harmonic. For the second harmonic, SSVEP slope for the DD group was reduced by 0.001µV/ms (shown in green), compared with both AM controls (shown in red), $t(51) = 2.67$, $p = .010$, 95% CI [0.0003, 0.002] and RM controls (shown in blue), $t(45) = 1.69$, $p = .033$, 95% CI [-0.0004, 0.003] however, group main effects were not statistically significant following Bonferroni corrections.



Supplementary Figure 2. Scalp topographies and waveforms for pre-target α power across groups. Analyses of interest revealed that pre-target α for AM controls (shown in red) was, 2.35μV lower on average than the DD group (shown in green), $t(51) = -2.52$, $p = .015$, 95% CI [-4.22, -0.48] and 2.07μV lower than RM controls (shown in blue), $t(45) = -2.13$, $p = .040$, 95% CI [-4.05, -0.10]. The DD group and RM controls did not differ. However, overall group main effects were not statistically significant following Bonferroni corrections.



Supplementary Figure 3. Scalp topographies and waveforms for contralateral N2 (N2c; **A**) and ipsilateral N2 (N2i; **B**) across groups showing the absence of any significant differences. **C.** Mean N2c latency across response hand. Peak latencies were 15.71ms earlier for left compared with right-handed responses for all participants however, the main effect for response hand was not statistically significant following Bonferroni corrections. *Note.* Error bars represent standard error of the mean.



Supplementary Figure 4. Scalp topography and waveforms for *β* (Beta) across groups indicating no significant group differences.

CHAPTER EIGHT: GENERAL DISCUSSION

This thesis sought to further our understanding of attention deficits in children with DD by addressing the heterogeneity frequently seen in the types of reading difficulties children with DD display and to provide clarity regarding the direction of the relationship between visual attention and reading acquisition. The objectives were twofold: 1) to investigate the role individual reading profile may play in explaining the variability in attention deficits in children with DD; and 2) to examine the direction of the relationship between attention and reading through comparisons to both age matched and reading matched controls. To address these, three studies were conducted. The first study investigated reported behavioural symptoms of attention deficits using the Conners 3 parent-rated ADHD symptom questionnaire (Chapter 5), the second explored the mechanisms underlying visual attention span deficits through computational modelling on the TVA paradigm (Chapter 6), and the third examined performance on a perceptual decision making task assessing visual attention using electroencephalography (Chapter 7).

This chapter briefly summarises the key findings from the three empirical studies of this thesis and explores the implications of this work, including theoretical implications for understanding attention deficits in children with DD and the practical recommendations for clinicians working with children with DD. An impetus for using reading profile to better understand attention in DD and to cater for individual needs is highlighted throughout. An overview of the strengths and an acknowledgement of the limitations of this work are presented, leading to suggestions for future research directions.

Summary of Results

The results of this research confirm that in addition to reading difficulties, children with a sole diagnosis of DD experience significantly more attentional and visual processing deficits than their typically-reading peers. On the whole, children with DD were rated as displaying more behavioural symptoms of inattention commonly associated with ADHD, slower uptake of visual stimuli (including both letters and symbols), and inefficient accumulation of motion information to make a perceptual decision about visual stimuli. Behavioural inattention and executive functioning problems as well as dysfunctional evidence accumulation were all shown to occur over and above reading ability (i.e., compared with reading matched controls). In contrast, poor processing speed associated with reduced visual attention span was related to reduced reading ability with comparable performances to younger, reading matched controls. Notably, across all studies, reading profile (i.e. relatively poorer lexical or sublexical reading skills) moderated the relationship between reading ability and attention in children with DD. Children with DD who had a reading profile characterised by relatively poorer lexical than sublexical skills (i.e., lexical DD) demonstrated greater attentional and decision making deficits across all three studies compared with those with relatively poorer sublexical than lexical skills (i.e., sublexical DD).

Theoretical and Clinical Implications of the Findings

Approaches to understanding DD.

Traditionally, neurodevelopmental disorders such as DD are conceptualised as a significant deviation from the typical trajectory of development in a particular domain of functioning. Under this framework, diagnosis is based on the presence of symptoms that tend to cluster together, most commonly defined according to DSM or International Classification of Diseases (ICD) criteria. A flow on effect of this approach is that our understanding of neurodevelopmental disorders is based on the assumption that children diagnosed with the same disorder present with equivalent difficulties in the same skills, falling into a discrete category of dysfunction. Therefore, research conducted under this rubric pays little attention to understanding individual differences or how symptoms may overlap across different disorders and, as a result, our understanding of the factors that contribute to a range of neurodevelopmental disorders is limited.

The results of the studies presented in this thesis illustrate that children with DD exhibit attentional and visual processing deficits that would not typically be considered characteristic of children with DD. Instead, many of these deficits would more commonly be used to describe children with ADHD. The results also show that these deficits vary considerably across children based on the types of reading difficulties they display, despite their common DD diagnosis. Together, these findings add to a growing literature documenting considerable variability both within, and between, a range of neurodevelopmental disorders (Thapar, Cooper, & Rutter, 2017). However, under existing categorical approaches, there is limited understanding regarding the factors that may account for this overlap in symptoms, especially considering the otherwise contrasting profiles of DD and ADHD in this case, or to explain why the attentional deficits shown here manifest differently across children with DD. There is also little guidance from both a clinical and research perspective as to how to classify children who might be diagnosed as having one disorder, in this case DD, who also present with isolated features of others (i.e., ADHD), or at least shared symptoms to a lesser degree of severity. By extension, there is a gap in our understanding of which treatments could be effective and for whom.

More recently, the scientific community has become increasingly aware of the utility of understanding comorbidity and heterogeneity in neurodevelopmental disorders, particularly in DD (Boada, Willcutt, & Pennington, 2012; McArthur et al., 2013). A push to explore other approaches to investigating neurodevelopmental disorders has followed. One such approach is the Research Domain Criteria (RDoC) initiative which describes neuropsychological and mental health disorders as the product of multiple factors of vulnerability in overlapping dimensions of genes, molecules, cells, and neural circuits which govern functioning (Insel, 2010). From a neurodevelopmental perspective, RDoC describes deviations from typical development at the lowest level of symptomatology with the aim of linking overt and measurable components of both normal and abnormal functioning to broader clinical phenomenology (Morris & Cuthbert, 2012). In this way, the RDoC framework seeks to explain the mechanisms of impairment at the lowest level of symptoms and then determine how these manifest at the behavioural, cognitive and emotional level, irrespective of top-down categorical models.

Although still being refined (see Mittal & Wakschlag, 2017 for a discussion), this approach has already been applied to other neurodevelopmental disorders including autism spectrum disorder (ASD) and ADHD (Ragland & Solomon, 2016), and has led to a better understanding of the shared features of these disorders as well as the potential neurobiological mechanisms that may explain this overlap (Solomon et al., 2009). It has also meant that these two disorders, which were once thought of as differential diagnoses, are now diagnosable in the same individuals according to the DSM-5. Therefore, approaches such as RDoC provide an appealing way in which to explore the findings presented here and, as González and colleagues (2018) contend, to better understand complex disorders such as DD.

What the Findings Add to Our Understanding of DD Using the RDoC Framework

Children with DD display a range of attentional deficits.

Firstly, the empirical studies herein showcase the domain of attention as assessed across multiple units of measurement - behavioural, cognitive and neural, with findings confirming that children with DD exhibit attentional deficits in a variety of ways. Although this thesis focused on attentional and visual processing deficits specifically, these results add to a substantial literature base describing a variety of deficits spanning multiple cognitive and behavioural domains in children with DD (Pennington, 2006). Together, the findings call for an understanding of DD that acknowledges the diversity of factors that could be contributing to poor reading outcomes. A multi-deficit perspective proposes that the development of any complex cognitive behaviour such as reading, requires the interaction of both biological and environmental factors that can range from being either protective or problematic (Pennington, 2006). Likewise, RDoC emphasises the importance of dimensionality, describing abilities along a continuum from typical to extreme (Cuthbert and Insel, 2013). Accordingly, disorders like DD are conceptualised as falling at the tail-end of the distribution, in this case on the dimension of reading. To date, the evidence suggests that what places a child with DD at the end of the reading spectrum is not necessarily a single, isolated factor. Instead, it is the culmination of a child's vulnerabilities across a range of domains where each child presents with a unique profile of deficits impacting on successful reading attainment (Perry, Zorzi, & Ziegler, 2018). The presence of attentional deficits in at least some of the children with DD studied here, suggests that attentional factors may increase the risk of reading difficulties in some but not all children with DD. Furthermore, evidence of co-occurrence of symptoms of ADHD in children with DD indicate that there may be risk factors that are shared across these disorders. For instance, quantitative methods examining the genetic similarities between monozygotic compared with dizygotic twin pairs have revealed that common genetic influences account for most of the phenotypic covariance between reading difficulties and inattentive symptoms of ADHD, whereas shared environmental factors, such as the family setting, predispose children with DD and/or ADHD to exhibit externalising behaviours (Willcutt, Pennington, & DeFries, 2000). With respect to genetic factors specifically, a number of different genetic risk loci have been identified in linkage studies as being common across both DD and ADHD (for a review see Germanò, Gagliano, & Curatolo, 2010). Hypotheses regarding the flow-on effects of these shared genetic factors pertain to their involvement in cerebral development, specifically hemispheric lateralisation and language processing, with neuroimaging studies revealing shared brain abnormalities in individuals with symptoms of both reading difficulties and attentional dysfunction. These include lower cerebellar volume (Castellanos et al., 2002; Eckert et al., 2003), reversed asymmetry of structures such as the planum temporale, caudate nucleus and frontal lobes (Foster, Hynd, Morgan, & Hugdahl, 2002; Pueyo et al., 2000) as well as less grey matter volume in the cerebellum (Kronbichler et al., 2008). However, the precise mechanisms by which these genetic differences govern the development of specific brain structures, the interaction of these biologically-driven factors with environmental influences and how these culminate to present as the common phenotypic features at the cognitive and behavioural level in both DD and ADHD is still unclear. Results presented in chapter seven of this thesis indicate that dysfunction in visual evidence accumulation may be a potential indicator of impairment at the neural level which could arise as a result of these brain abnormalities in development. These findings provide a neural basis for slowed processing of visual material which likely reflects dysfunction in attentional engagement of feed-forward-feedback loops driven by the parietal lobe as part of the dorsal magnocellular processing route, thus providing a mechanistic account of poor outward performance. Although we can only speculate as to the precise cause of inefficient evidence accumulation in DD, the dorsal magnocellular processing route requires the contribution of a range of cortical networks (Bullier, 2001). Accordingly, these results may explain evidence of deficits across multiple cognitive domains in DD (i.e., attention, magnocellular function, temporal processing, automaticity and cerebellar engagement; Peterson & Pennington, 2015) and therefore bridge several different theories regarding the causes of DD. Whether the same dysfunction is also evident in children with ADHD and whether this can be linked to genetic overlap to indicate a shared mechanism of impairment is unknown but could be elucidated by future RDoC research. It is also important to note that the RDoC approach acknowledges the possibility that the same clinical symptoms may not have the same underlying mechanisms (Casey, Oliveri, & Insel, 2014). So, although our children with DD present with co-occurring ADHD symptoms, these may arise from a different origin compared with those that are present in children with a primary diagnosis of ADHD. Accordingly, more research is needed to identify the underlying factors explaining attentional deficits in children with DD and how these may be similar or different from those found in children with ADHD and to then describe their influence on reading acquisition.

Not all attention deficits are unique to DD.

A central tenet of this thesis is that poor reading ability subsequently reduces a child’s exposure to text which may result in inadequate opportunities to refine supplementary skills such as attention. As a result, it is unclear whether many of the attentional deficits described in the literature reflect a cause, or an effect, of reduced reading ability in DD. This may be a major reason for the disagreement among researchers. As Huettig, Lachmann, Reis and Petersson (2017) note, most known deficits associated with reading difficulties in DD also occur in “normal” illiterate or low literate adults who have received little to no reading instruction suggesting they may arise secondary to suboptimal reading experiences. Therefore, they may not be unique to those with DD who struggle despite adequate reading opportunities. Our findings specifically indicate that behavioural indices of inattention and executive dysfunction as well as neural markers of poor evidence accumulation are unique to DD, whereas hyperactivity and slowed uptake of visual material appears to be related to reduced reading ability and therefore may be evident in all children with immature reading systems. Firstly, this finding highlights a more nuanced relationship between attention and reading than first thought. It also contributes to a growing literature that emphasises the importance of attention for reading (Vidyasagar, 2019). At a higher level, it prompts the revision of both attention and reading theories which to date have largely been conceptualised separately. For instance, the attention models put forth by Corbetta and Shulman (2002) and Posner and Petersen (1990) do not consider data that shows reading habits such as reading direction have an influence on spatial attention (Chokron & Imbert, 1993; Kermani, Verghese, & Vidyasagar, 2018). Although some researchers have presented hypotheses regarding the potential mechanisms through which various aspects of attention can facilitate reading (Ans, Carbonnel, & Valdois, 1998; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Pammer & Vidyasagar, 2005; Valdois, Bosse, & Tainturier, 2004), no one model has been capable of explaining the various findings in the literature across multiple domains of attention within a single cohesive framework. Attention and reading models also frequently describe abilities once they are established, primarily based on data from adults. Therefore, less is known about the typical development of these abilities throughout children or how this may go awry in cases of DD. With respect to attention, this is further complicated by the lack of conceptual clarity and the overlap that attentional skills have with other cognitive constructs such as executive function, making consensus among researchers difficult to achieve (see Plude, Enns, & Brodeur, 1994 for a review). Nonetheless, developmental studies largely provide evidence that the development of both attention and reading abilities are multistage processes in which different skills develop at different times, beginning in infancy and continuing at least until adolescence (Pozuelos, Paz-Alonso, Castillo, Fuentes, & Rueda, 2014; Rueda et al., 2004). Accordingly, each new stage of skill development can either result in a breakthrough or a breakdown with a deficit that occurs early in development giving rise to a more complex cascade of problems than one that occurs later as different brain regions and cognitive networks mature and interact over time. The findings presented here call for a more cohesive description of how attention and reading interact at these different stages. For instance, our data suggests that it is unlikely problems with behavioural inattention, executive dysfunction or inadequate integration of visual information are simply an outcome of poor reading exposure and experience. Instead, it appears that these deficits impact on the adequate acquisition of reading and therefore may be contributing to poor reading outcomes uniquely in children with DD. Hyperactive behaviour and reduced visual processing speed on the other hand, may be a consequence of reduced reading exposure. Thus, reading may play an integral role in helping refine these abilities throughout development. Here it is also important to note that DD is typically not evident until school-age. This is particularly pertinent to understanding the timeline of changes that occur during childhood and how reading instruction might interact with the development of other supplementary skills such as attention to support either successful acquisition in typical circumstances or impede on reading to result in DD. Understanding attention and reading development in this way aligns with the principles of RDoC which emphasise the importance of understanding differences in the development of various skills over time as well as accounting for sensitive periods where the effects of particular experiences have a stronger influence on brain and behaviour. It also acknowledges the differences between brain networks that are developed and those that are still developing with the understanding that developed networks will respond differently to new experiences than those that are still undergoing change (Casey et al., 2014).

Attention deficits vary as a function of reading profile.

An important problem in studies of attention in children with DD is that findings are notoriously variable and conflicting across studies which initially provided evidence against visual deficits in DD (Vellutino, 1987). However, many researchers have since recognised the considerable heterogeneity in reading skills that is frequently evident in DD samples and have therefore sought to explain mixed findings in terms of individual differences. On the whole, visuospatial attentional deficits have commonly been associated with individuals with DD who present with prominent sublexical deficits (Facoetti et al., 2006; Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012) whereas reductions in visual attention span and slowed naming of visual stimuli have been reported in those with intact sublexical skills but poor lexical abilities (Bosse & Valdois, 2003, 2007; see also chapter 3 of this thesis for a review). Similarly, the studies presented here demonstrate that the relationship between attention and reading varies systematically as a function of the type of reading difficulties each child displays (i.e., their individual reading profile). In our cohort and using our measures, relatively poorer lexical compared with sublexical skills was associated with significantly more severe attentional deficits and the greater the disparity between lexical and sublexical skills, the greater the associated attentional deficit. Specifically, reduced visual attention span (driven by slowed processing speed) and inefficient processing of visual motion stimuli was more pronounced in those with poorer lexical compared with sublexical reading abilities. These children were also more likely to be rated as displaying behavioural symptoms of attention dysfunction (inattentiveness and executive dysfunction).

In the context of past research, these results are in keeping with a visual attention span deficit being specific to children with intact sublexical skills (Bosse & Valdois, 2003, 2007). They are also consistent with evidence that inattentive symptoms of ADHD are more prevalent in DD samples than hyperactive symptoms (Willcutt & Pennington, 2000) and that lexical reading deficits may represent an overlapping symptom of reading dysfunction in both DD and ADHD (de Jong et al., 2012). Here we extend these findings by showing that ineffective information processing of visual material evident even at the neural level is also specific to children with relatively poorer lexical than sublexical abilities. Accordingly, it appears that there is a specific subset of children with DD who are at greater risk of attentional problems and that they can be identified on the basis of the types of reading difficulties they display in addition to their below age-appropriate reading.

From a theoretical standpoint, the findings suggest different components of reading may have different attentional requirements. For instance, one could argue that the attentional deficits described in chapters 6 and 7 impact on the size of a child's attentional window (due to the reduced speed and efficiency with which they are able to accumulate visual information). As a consequence, this difficulty likely impacts on activation of global processing routes according to the MTM model and engagement of the lexical route of reading as described in the DRM as these children are unable to take in the word as a whole. Combined with the findings presented earlier, it appears that some of these deficits may be contributing to inadequate development of lexical skills in these children whereas others may be an outcome of their poorer relative lexical abilities.

Although on the basis of this it would be parsimonious to conclude that individuals with DD have either intact or impaired attention according to their reading profile, the picture is likely to be far more complex. For instance, a dissociation between different 'subtypes' of DD and attention deficits has been refuted in other studies (Lukov et al., 2015). We also did not see evidence of visuospatial deficits in our sample and thus cannot confirm other findings linking sublexical reading impairments to dysfunctional allocation and control of attentional resources across space. A key differentiating factor is that in our studies, reading profile was measured as relative lexical and sublexical skills on a continuous scale. Accordingly, our results pertain specifically to attentional variation on a spectrum rather than between subgroups of individuals classed as having a particular type of DD. This is particularly important as word reading requires the contribution of both lexical and sublexical routes and thus it appears that in an individual it is the relative strength of these skills, rather than the absolute presence of a deficit in one or the other, that is associated with attentional problems. This may help to explain some of the mixed findings in the literature as studies have tended to categorise based upon the absence or presence of deficits in one reading skill without incorporating both lexical and sublexical abilities as done here.

Practical Recommendations

Incorporating measures of attention at assessment.

The findings of this thesis also have critical implications for clinical practice. Firstly, they highlight the importance of including measures of attention when assessing children with, or suspected of having, DD. At present, the lack of clear evidence-based guidelines means that the diagnostic pathway for DD may take many different directions as clinicians frequently adopt their own battery of tests and tend to focus on reading-specific tools (Vellutino, Fletcher, Snowling, & Scanlon, 2004). The results here highlight that attentional factors need to be considered in addition to indices of reading performance. Incorporating measures of attention can help identify issues that may be impacting on a child's abilities that would otherwise be overlooked by adopting standard testing batteries and may provide greater insight into a child's functioning in both the educational and home environment.

Using reading profile to identify children at risk and to tailor treatment.

The benefits of using assessment tools grounded in theoretical models such as the CC2 to index reading profile has been showcased across all three empirical studies in this thesis. Subsequent evidence that not all children with DD present with equivalent attentional difficulties speaks strongly to the importance of characterising a child's individual strengths and weaknesses. Specifically, the findings from behavioural ratings in chapter 5 illustrate the importance of not only defining the severity of reading difficulties in DD relative to typically developing peers, but also describing the specific type of difficulties with which a child presents to identify those who are at greatest risk of additional inattentive behaviour and executive dysfunction. The results also suggest that assessing reading profile in this way can be helpful to not only inform which remediation methods may be useful to target specific sub-components of reading, but to also determine who is at greatest risk of additional attentional problems and could therefore benefit from treatment or management strategies that also target attention. At present, there is limited consensus as to whether targeting both reading and attention difficulties simultaneously or treating one to see if subsequent benefits are seen in the other, is preferable in cohorts of children with DD also presenting with symptoms of ADHD (Tamm et al., 2017). This is further complicated by the frequently fragmented approach to treatment that these children are likely to receive. Nonetheless, recent evidence indicates that although there is no clear additive value of administering both pharmacological ADHD medication with reading remediation in children (i.e., simultaneously treating both attentional and reading difficulties does not result in greater improvements in either outcome compared with treating them in isolation), combined treatment enables remediation of both ADHD and reading symptoms concurrently and is therefore more time-efficient. Accordingly, simultaneous delivery would still be recommended over treating symptoms of each disorder separately (Tamm, et al., 2017). Accordingly, assessing individual reading profile in children with DD can help identify who may benefit from combined treatment approaches, thereby facilitating the provision of tailored treatment plans and compensatory strategies that can best support individual needs. On a wider scale, this has significant ramifications for streamlining the provision of clinical services, ensuring that resources are provided to those who are most likely to require them and that they are delivered as early as possible to optimise outcomes.

Strengths, Limitations and Future Directions

Measures of attention.

The studies contained within this thesis consistently demonstrate the utility of examining attention in children with DD using a variety of methods. Employing a variety of measurement modalities and techniques was essential to illustrate the wide-ranging nature of attention deficits in DD and the tasks used had specific strengths leveraged to test each respective study aim. However, there were also some inherent limitations of the measures used that should be addressed in future research. For instance, although behavioural measures of attention such as the Conners 3 are designed to examine the outward manifestation of attention dysfunction in real-world scenarios, ratings can be influenced by a variety of external factors so may not be the direct result of attentional problems *per se* (Barkley, 1988). On the other hand, computational and experimental paradigms such as the TVA and perceptual decision making tasks like the random dot-motion task used here have limited generalisability to real-world situations, thus restricting their ecological validity and translation into clinical practice. Although an ambitious suggestion, researchers should continue to strive towards developing measures that are both grounded in theoretical knowledge but have good clinical utility by translating experimental tasks into clinical tools. This is one significant advantage of the CC2 measure used to ascertain reading profile in this thesis, as it has strong roots in the DRM of single word reading but is also designed to be easily administered *in vivo* by both teachers and clinicians. Given attention is not a unitary construct, there is also a need for DD researchers to consider the various contributory processes that influence outward performance in their approach to measurement and task design. In line with the rationale for the experimental measures used in the studies described in chapters 6 and 7, robust paradigms that isolate underlying contributory processes, or behavioural measures that are comprehensive in their scope such as combining multiple reporters across a variety of settings, are useful as they enable the examination of specific components of attention that may be impaired in DD and attempt to pinpoint specific mechanisms of impairment. Not only will it be important to verify the relationship between attention and reading shown here using a wider variety of tasks and methodologies in DD cohorts, it will also be important to continue refining our understanding of how these findings may apply to other aspects of attention at a more proximal level. In DD research, this should also encompass different modalities including attention in the auditory domain given evidence that attentional deficits may not be confined to visual stimuli (Lallier, Donnadieu, & Valdois, 2013).

Matching techniques.

In her opinion piece, Goswami (2015) provides an excellent overview of the limitations of both sensory and attentional hypotheses of DD and gives various methodological suggestions for research aiming to disentangle cause from effect in DD. Accordingly, a significant advantage of the studies in this thesis was the inclusion of the reading matched group as comparisons to younger, typically reading participants providesd important insight into the relationship between reading ability and the development of skills that supplement reading such as attention, otherwise not captured with traditional age matched designs. However, matching on only one key measure of reading ability (i.e., single word reading accuracy) was a limiting factor in these studies as this does not take into account the range of reading skills, including reading speed, fluency and spelling ability. There are also some arguments that reading-level designs fail to account for other related factors such as maturation (see Van den Broeck & Geudens, 2012). Although matching participants on a combination of reading skills and demographic variables would be ideal, it is acknowledged that this adds to the recruitment burden as it makes enlisting large samples even more difficult. Nonetheless, future research capturing reading ability more comprehensively will ensure a more tightly controlled matching methodology and more persuasive findings as a result.

Although various control groups can be used as analogues of development, we can also only speculate as to how those with DD deviate from their typically developing counterparts using these comparisons. Longitudinal studies that specifically track the development of reading acquisition and attention in both typical and atypical readers over extended time periods are therefore critical to clarify the nature of this relationship. Researchers are thus encouraged to continue to account for reading ability and reading experience in the future by using these approaches to add to the findings presented here. One particularly inviting avenue of research would be to further investigate whether reading profile may be useful in predicting early attentional and perceptual vulnerabilities in preschool children at risk, or showing early signs, of reading difficulties. Understanding the reading-attention relationship in this way is particularly pertinent to informing how anomalies in these domains may influence each other and predict later functioning.

Accounting for individual differences.

A significant strength of this thesis is that addressing the issue of heterogeneity was at the forefront of each study design. The approach used to characterise individual reading profile was novel and grounded in a well-established theoretical model of reading. However, a related limitation is that although the CC2 has been established as a reliable and valid measure of the DRM of single word reading (Castles et al., 2009), characterising reading profile as relative lexical to sublexical skills does not necessarily account for what is considered typical variation in these skills. There are significant advantages to capturing reading skills along a continuum as was done here, including ensuring that participants presenting with different abilities are not crudely clustered to form discrete sub-groups and that the relative contribution of both pathways are considered. However, further research is needed to validate the use of relative lexical and sublexical skills as a single indicator of reading profile, and to establish the cut-points at which skill discrepancy indicates either superiority or deficiency. Future work should also seek to replicate these findings in samples of non-English speaking participants to determine their generalisability across orthographies of varying transparency.

Researchers are increasingly arguing that the heterogeneity of DD may prevent a single genetic or cognitive cause from being determined. To highlight this point, Pennington (2006, 2012) argues that multiple genetic and environmental risk factors combine to impede on typical reading acquisition in DD. This also places children at risk of other associated problems, explaining the high degree of overlap DD has with other neurodevelopmental disorders. As a result, it is possible that different individuals will likely respond to different treatments (Ring & Black, 2018). On the basis of the findings presented herein, it appears that reading profile may have the potential to provide unique insight into which children with DD might benefit from remediation programs that target attention and perceptual decision making. In fact, researchers are making headway in this space with promising outcomes being reported in the DD literature through the use of videogames (see Peters, Losa, Bavin & Crewther, 2019 for a review). Nonetheless, it is important to acknowledge that it is unlikely that reading profile is the only indicator of individual variability in DD especially as the link between DD subtypes and attentional performances are still hotly debated (Lukov et al., 2015). In addition to studying the relevance of reading profile across a broader range of cognitive functions in DD, future work should also aim to uncover the various vulnerabilities that culminate to result in DD by applying dimensional approaches across larger cohorts.

Sampling considerations.

In terms of the participant sample, the strict recruitment and screening strategies adopted were designed to ensure that participants met criteria specified by the DSM-5 and did not present with any additional diagnosed comorbidities. As an advantage, this allowed examination of attention deficits in what was considered a relatively 'pure' DD sample. Accordingly, the evidence of considerable attentional deficits in a cohort of children that were not flagged as having attentional problems further emphasises the need to look at symptoms of attention dysfunction that present at a sub-clinical level but can still have an influence on functioning. However, not including children with additional comorbid diagnoses meant that we were unable to examine those with DD who also fall at the higher end of the attention-deficit spectrum and therefore may have differing presentations. Due to the strict sampling criteria, the groups used in the study were also relatively small. Future research should seek to widen the scope of recruitment to provide greater power whilst also noting important information regarding comorbidities to detect potentially subtle but important differences between individual children with DD. These 'mixed cohorts' will more closely reflect the variable nature of how DD presents in a real-world setting and thus also have greater application to clinical practice. The outcomes of research conducted in this way would also more closely align with the objectives of the RDoC approach and contribute to a dimensional understanding of DD. Relatedly, the results of the empirical studies here can also only be generalised to individuals with DD who fall within a select range (i.e., between 9 and 14 years old). Although it is acknowledged that replication will be required to verify the findings across other cohorts, this age range is fairly typical for paediatric research as it allows generalisation to late primary and early secondary school age children. It is also the age at which many children are commonly identified and diagnosed with learning difficulties (Louden et al., 2000). As some of the tasks (i.e., particularly the symbol condition of the TVA paradigm and the random dot-motion task with concurrent EEG recording) would have been overly demanding for many younger children, the lower age criterion was set at 9 years. However, it would be useful for future studies to consider modifying these paradigms for application in younger groups, especially as considerable focus is now being placed on early identification and remediation of reading, and associated difficulties, within the first few years of formal education (Hordacre, Moretti, Spoehr, 2017).

EPILOGUE

Children diagnosed with DD face significant barriers within the current educational setting. They are often assumed to be lazy, unmotivated or intellectually incapable (Riddick, Sterling, Farmer, & Morgan, 1999). There are also many children with DD who present with attentional impairments placing them at an even greater risk of poor long-term outcomes (Willcutt et al., 2001). This thesis has explored the nuanced relationship between attention and reading in children with DD. Although issues around heterogeneity and directionality are frequently acknowledged as a limitation in the literature, it is often difficult to manage this variability in practice and therefore much more appealing to describe performance at a group level. The series of studies presented here provide a way in which researchers and clinicians can use an index of reading profile to help dissect this heterogeneity and identify children at-risk of attentional problems. The research also showcases the use of novel matching methodologies to clarify the complex, bidirectional relationship between reading and attention. Given the importance of early learning for later academic and occupational achievement (Duncan et al., 2007), it is essential that we continue research efforts to advance our understanding of the various factors that contribute to DD and search for ways that reading difficulties may be remediated. As a by-product, we can prompt a substantial shift in the perspectives and outlook of children with Specific Learning Disorders more broadly, and most importantly, inform ways that we can better tailor our approach to meet the educational needs of all Australian children, setting standards for children worldwide.

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