The Role of Visual Attention in Reading: Implications for Developmental Dyslexia

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List of Abbreviations

ANOVA	Analysis of Variance
AVG	Action Video Game
AVG+	Enhanced Action Video Game
AVG-R	Regular Action Video Game
CA	Chronological-age-matched
CTOPP	Comprehensive Test of Phonological Processing
DD	Developmental Dyslexia
DDT	Direction Discrimination Training
eSMD	Estimate Standard Mean Difference
FC	Fixation Count
FD	Fixation Duration
FFT	Flicker Fusion Threshold
M	Magnocellular
MD	Magnocellular-Dorsal
MD-Dyslexic	Magnocellular-Deficit Dyslexic
MT-Dyslexic	Magnocellular-Typical Dyslexic
Non-AVG	Non-Action Video Games
P	Parvocellular
RA	Reading-age-matched
RAN	Rapid Automatic Naming
RAP	Reading Acceleration Program
RCPM	Ravens Colored Progressive Matrices
RSPM	Ravens Standard Progressive Matrices
RD	Reading Difficulties

ROBINS-I	Risk of Bias in Non-randomised Studies of Interventions
ScD	Saccade Duration
SMD	Standard Mean Difference
SS	Standard Score
TDT	Texture Discrimination Training
VHSS	Visual Hemispheric Specific Stimulation
VPT	Visual Perceptual Training
YARC	York Assessment of Reading for Comprehension

Publications and Manuscripts Related to this Thesis

Chapter 2

Peters, J. L., De Losa, L., Bavin, E. L., & Crewther, S. G. (2019). Efficacy of dynamic visuo- attentional interventions for reading in dyslexic and neurotypical children: A systematic review. *Neuroscience & Biobehavioral Reviews*, *100*, 58-76.

Chapter 4

Peters, J. L., Bavin, E. L., Brown, A., Crewther, D. P., & Crewther, S. G. (2020). Flicker fusion thresholds as a clinical identifier of a magnocellular-deficit dyslexic subgroup. *Scientific Reports, 10*(1), 21638. doi:10.1038/s41598-020-78552-3

Chapter 5

Peters, J. L., Bavin, E. L., & Crewther, S. G. (2020). Eye movements during RAN as an operationalization of the RAN-reading “microcosm”. *Frontiers in Human Neuroscience,* 14(67). doi:10.3389/fnhum.2020.00067

Presentations Related to this Manuscript

2019

Peters, J. (2019, November). *Fruit Ninja to improve reading: An action video game treatment for dyslexia.* Paper presented at the Australasian Cognitive Neuroscience Society Conference, Launceston. **(Oral Presentation)**

Peters, J., De Losa, L., Bavin, E. L., Crewther, S. (2019, August). *Efficacy of dynamic visuo-attentional interventions for reading in dyslexic and neurotypical children: A systematic review*. Poster presented at the Second James Lance – Peter Goadsby Annual Symposium, Melbourne. **(Poster Presentation)**

Peters, J. (2019, August). *The Role of Visuo-Attention in Reading: Pre-Submission Milestone Presentation.* Presented at the Department of Psychology and Counselling Higher Degree by Research Seminar, La Trobe University, Melbourne. **(Oral Presentation)**

*Peters, J. (2019, September). *A role for visual attention in reading*. Paper presented at the College of Clinical Neuropsychologists (CCN) Student Research Symposium, La Trobe University. **(*Invited Oral Presentation)**

Peters, J., Brown, A., Bavin, E. L., Crewther, S. (2019, May). *Both low and high contrast flicker fusion thresholds differentiate dyslexic and typically developing children*. Poster presented at the Vision Sciences Society (VSS) Conference, Florida. **(Poster Presentation)**

2018

*Peters, J., De Losa, L., Bavin, E. L., Crewther, S. (2018, December). *Efficacy of dynamic visuo-attentional interventions for reading in dyslexic and neurotypical children: A systematic review*. Paper presented at the School of

Psychology and Public Health 2018 Research Festival, Melbourne**. (Oral Presentation)**

Peters, J., De Losa, L., Bavin, E. L., Crewther, S. (2018, November). *Efficacy of dynamic visuo-attentional interventions for reading in dyslexic and neurotypical children: A systematic review.* Poster presented at the 8th Australasian Cognitive Neuroscience Society Conference, Melbourne. **(Poster Presentation)**

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2017

Peters, J., Bavin, E. L., De Losa, L., Ramzee, F. R., Thomas, T., Alihos, C., & Crewther, S. (2017, November). *Eye movement patterns during fluent reading in primary school children: Preliminary findings*. Poster presented at the 7th Australasian Cognitive Neuroscience Society Conference, Adelaide. **(Poster Presentation)**

Crewther, S., Peters, J., Goharpey, N., Taylor, J., Mungkhetklang, C., Crewther, D., & Laycock, R. (2017, May). *Eye movements during rapid naming tasks predict reading ability*. Poster presented at the Association for Research in Vision and Ophthalmology Conference, Baltimore. **(Poster Presentation)**

2016

Peters, J., Taylor, J., Crewther, D., Cross, A., & Crewther, S. (2016, July). *Relation of rapid automatized naming (RAN) and eye movements in learner readers*. Poster presented at the 12th Asia-Pacific Conference on Vision (APCV), Fremantle. **(Poster Presentation)**

Thesis Abstract

Developmental dyslexia is characterized by significantly impaired reading ability, and affects 10% of the population. While impaired phonological awareness is currently the predominant theory, those with dyslexia have also been shown to have deficits in visual attention and temporal visual processing thought to be associated with the faster conducting Magnocellular visual pathway. Hence, in this thesis the aim was to investigate the contribution of the magnocellular pathway to reading ability in dyslexic and neurotypical children, via eye movements and visual temporal processing thresholds. A systematic review of the intervention literature revealed that reading skills can be improved significantly via dynamic visual attention training, including Action Video Games (AVGs), without the need for explicit phonological, orthographic or reading instruction. The empirical research conducted and reported in the thesis demonstrated in a subgroup of children with dyslexia (~54% of the sample), deficits in low and high contrast achromatic flicker fusion thresholds, indicative of slower neuronal recovery following repetitive visual stimulation and associated impairments in temporal processing. Eye movement patterns, accepted as surrogates of the temporo-spatial placement of attention, were highly predictive of rapid naming and reading performance. The dyslexic group required a greater number of fixations and longer fixation durations compared with age-matched typical readers, suggesting reduced efficiency in attending to and extracting information during fixations. AVG training significantly improved reading accuracy, rate and comprehension in the children with dyslexia after only five hours. Those with lower flicker fusion scores before AVG training showed the greatest improvement in temporal processing, and improved low contrast flicker fusion significantly predicted reading accuracy improvements. Overall, these findings highlight the role of faster visual attentional processing in reading and offer novel insights into the value of training visual attention and the effectiveness of using AVGs in intervention programs for dyslexia.

Statement of Authorship

Except where reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis submitted for the award of any other degree or diploma. No other person's work has been used without due acknowledgement in the main text of the thesis. This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution.

This thesis includes four co-authored manuscripts which are published or have been submitted for consideration at peer-review journals. The inclusion of co-authors across these chapters reflects work that originated from active collaboration between researchers and acknowledges input into team-based research. Nonetheless, the theoretical basis, data collection and analysis, and written material of this thesis were the principal responsibility of the candidate, under the supervision of Professor Sheila Crewther and Emeritus Professor Edith Bavin.

All research procedures within this thesis were approved by the La Trobe University Human Research Ethics Committee (UHEC 16-121), the Victorian State Department of Education (2017_003294), and Catholic Education Melbourne (CEM 0589).

Signed:

Jessica Peters

Date: 21st December 2020

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CHAPTER 1

Introduction and Thesis Overview

1.1 Background

Developmental dyslexia is a neurodevelopmental disorder that is characterized by impairments in reading accuracy, rate, comprehension and fluency, and affects ~10% of the population (American Psychiatric Association., 2013). Those with dyslexia commonly experience significant educational and occupational disadvantage despite adequate intelligence and educational opportunity (Lyon, Shaywitz, & Shaywitz, 2003), and are at higher risk of mental health difficulties, both co-occurring and secondary to their reading deficits (American Psychiatric Association., 2013; Humphrey & Mullins, 2002; Sahoo, Biswas, & Padhy, 2015). Thus, investigations into the processes that underpin dyslexia are vital to the development of novel, empirically based interventions and to improved quality of life of those with dyslexia.

Yet, despite more than a century of research, dyslexia is still not entirely understood and gaps in the literature remain. As such, the causal bases of dyslexia remain a topic of considerable controversy and debate (Gori & Facoetti, 2014). An impairment in phonological awareness (i.e., a deficit in awareness and discrimination of speech sounds) has been the most accepted theory of dyslexia since the 1970’s and the focus of many remediation efforts (Vellutino, Steger, & Pruzek, 1973). Yet, causal evidence is equivocal (see Castles & Coltheart, 2004) and several other theories argue that phonological deficits characterize one of several distinct dyslexia subtypes (Boder, 1970; Castles & Coltheart, 1993; Wolf & Bowers, 1999). Indeed, around half of dyslexic children do not experience phonological impairments (Elhassan, Crewther, & Bavin, 2017; O'Brien, Wolf, & Levett, 2012) and a third do not benefit from phonological interventions (Torgesen, Morgan, & Davis, 1992; Vellutino et al., 1996; Whiteley, Smith, & Connors, 2007). Moreover, of those whose ability to decode words is improved, very few with dyslexia ever learn to read with fluency and automaticity (Lefly & Pennington, 1991; Shaywitz et al., 1999). This suggests that the traditional view of dyslexia as a uniquely phonological disorder is inadequate, particularly with regard to fluency and rate of reading, and indicates a need for investigation of other aetiological factors.

The most likely alternative is vision-based (Lovegrove & Brown, 1978), as had been the predominant theorized aetiology from the time of Rudolf Berlin, who coined the term dyslexia in 1887, until the 1970's (Vellutino, Fletcher, Snowling, & Scanlon, 2004; Wagner, 1973). Since Lovegrove's seminal papers (Lovegrove & Brown, 1978; Lovegrove, Martin, & Slaghuis, 1986; Lovegrove, Bowling, Badcock, & Blackwood, 1980), many studies have suggested that the temporal rate of visual processing must be considered in dyslexia, and in particular, that of the faster conducting and transient Magnocellular (M) pathway, which is accepted to drive visual attention and motion processing action (Archer, Pammer, & Vidyasagar, 2020; Badcock & Lovegrove, 1981; Crewther, Crewther, Barnard, & Klistorner, 1996; Livingstone, Rosen, Drislane, & Galaburda, 1991; Lovegrove, 1996; Martin & Lovegrove, 1987; Stein, 2019; Talcott et al., 1998). Hence, this thesis aims to address several gaps in the literature pertaining to dyslexia and the contribution of rapid visual attentional processing of the M stream and as novel targets for intervention, with an emphasis on clinically translatable findings.

1.1.1 The Role of Visuo-Attention in Reading and Dyslexia

Research involving rapid processing in dyslexia has frequently identified impairments associated with visual attentional mechanisms (Gori & Facoetti, 2014; Laycock, Crewther, & Crewther, 2012; Rutkowski, Crewther, & Crewther, 2003). Deficits in the rate of activation of visual attention are found in dyslexia (Barnard, Crewther, & Crewther, 1996), resulting in eye movements that are slower to process visual information, and engage and disengage at each fixation. Similarly, those with dyslexia display ‘sluggish attentional shifting’, affecting the rate of eye movement shifting to the next target when viewing rapid stimuli sequences, and impacting upon perception of visual stimuli and ability to blend letters in words (Krause, 2015; Lallier et al., 2010). Deficits in the orienting and focusing of visual spatial attention are also evidenced, impairing the ability to selectively extract and process the spatial relationship of visual information from a specific region of space (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Laycock, Crewther, Fitzgerald, & Crewther, 2009; Treisman, 1988; Vidyasagar & Pammer, 2010). During reading, these impairments to visual attention would be expected to result in difficulties filtering out irrelevant adjacent stimuli (e.g., visual noise), reducing the sensitivity (i.e., spatial resolution) needed to distinguish and segment text into letter-strings (i.e., letter parsing) and consequentially the speed of visual processing (Facoetti, 2012; Facoetti et al., 2006; Gori & Facoetti, 2014; Krause, 2015). Impairments in early processing of visual stimuli would then impact other cognitive processes required in reading, such as orthographic recognition of graphemes and their phonemic translation (Vidyasagar & Pammer, 2010). Thus, impairments in the rate of visual attention shifting may help to explain why reading often remains slow and laborious for those with dyslexia, and so will be explored further within the research conducted in this thesis.

1.1.2 A Magnocellular Basis for Visual Attention Deficits in Dyslexia

The Magnocellular-Dorsal (MD) theory of dyslexia is the most common neurobiological explanation for the visual attentional impairments seen in dyslexia (Klistorner, Crewther, & Crewther, 1997; Laycock & Crewther, 2008; Stein & Walsh, 1997). As shown in Figure 1, the large and fastest conducting magnocellular ganglion cells of retina project cortically via the lateral geniculate nucleus to layer 4 Cα of the primary visual cortex (V1). M cells also project subcortically via superior colliculus and pulvinar, to the motion processing cortical area, MT/V5, of the dorsal visual stream (Maunsell & Newsome, 1987), and to the emotional attention processing amygdala (Archer et al., 2020; Maunsell & Newsome, 1987). The dorsal stream, which is predominantly M cell driven (Pina Rodrigues et al., 2017; Ungerleider & Mishkin, 1982), projects forward from V1 through a hierarchy of bidirectionally interconnected areas to the posterior parietal cortex (PPC) and the dorsolateral pre-frontal cortex (PFC), which helps direct eye movements during reading, forming the fronto-parietal attention network (Archer et al., 2020). Thus, dysfunction of M input of the dorsal visual stream would result in impairment of the goal directed parietal-fronto-attention network (Livingstone et al., 1991; Stein & Walsh, 1997), and therefore the aforementioned visual attentional deficits seen in dyslexia.

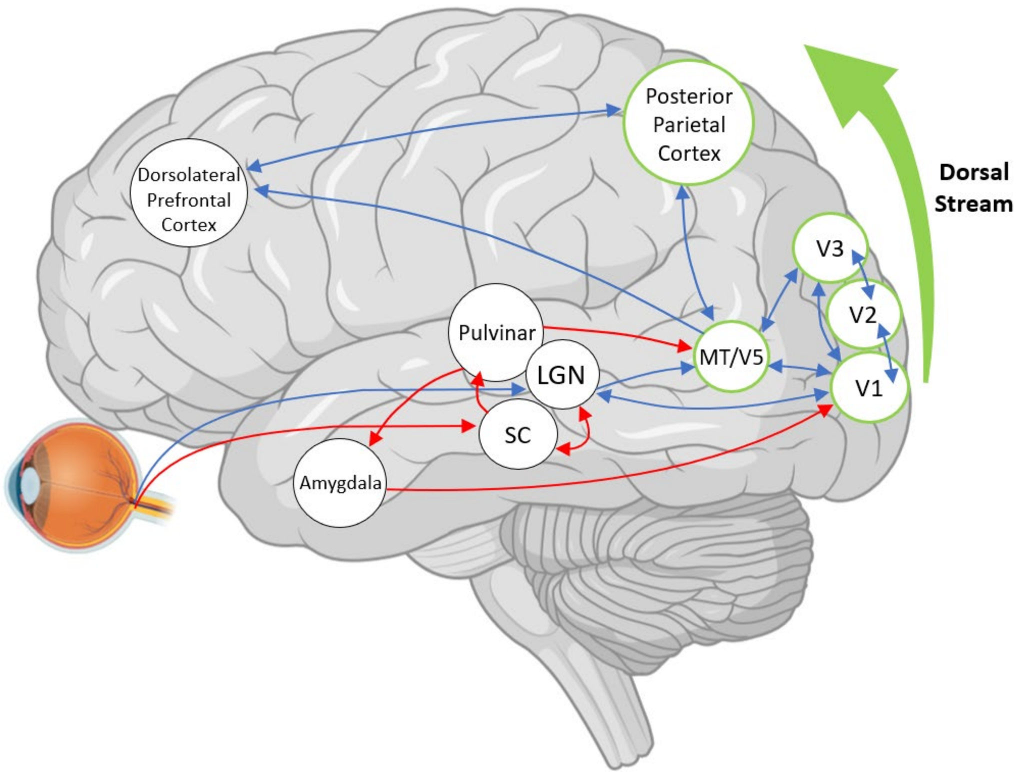

Figure 1. The Magnocellular Stream.

In comparison with the smaller retinal ganglion cells of the 'sustained' parvocellular (P) pathway, the large M cells respond rapidly and transiently, even at low luminance, achromatic information and low spatial frequencies (Bruce, Goldberg, Bushnell, & Stanton, 1985; Stein, 2019; Stein & Walsh, 1997; Talcott et al., 1998). On psychophysical testing designed to isolate M functioning, both children and adults with dyslexia are typically found to be less sensitive than typical readers on tasks with high temporal and low spatial frequencies (e.g., motion coherence and contrast sensitivity tasks; Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Eden et al., 1996; Kevan & Pammer, 2009; Laycock et al., 2012). Yet, typical performance is typically seen on tasks designed to preferentially stimulate the P pathway (e.g., involving colour or form; Chase & Jenner, 1993; McLean, Stuart, Coltheart, & Castles, 2011), further supporting the view that dyslexic individuals have a specific impairment in the magnocellular pathway of the visual system.

1.1.3 Controversies and Gaps in the Literature

Despite evidence of visual attention and M pathway deficits in dyslexia, their role in dyslexia remain somewhat contentious and the exact nature of their relationship to dyslexia is not fully elucidated (Skottun, 2000). For instance, Goswami (2015) contended that sensory and attentional impairments are a consequence and not a cause of reading deficits, and that oculomotor and visual attention differences between dyslexic and typical readers could simply reflect reduced reading experience. The author also suggested that phonological deficits underlie attentional deficits (Goswami, 2015), though other research proposes that attentional and magnocellular deficits may actually underpin phonological impairments in dyslexia (Elhassan et al., 2017; Facoetti et al., 2010; Laycock et al., 2009; Vidyasagar & Pammer, 2010). More specifically, the MD Theory of dyslexia has also been criticized due to inconsistency in psychophysical findings, with some studies finding dyslexic participants perform comparably to typical readers while the results of others suggest that impairments are in general processing not exclusive to the M stream (Contemori, Battaglini, Barollo, Ciavarelli, & Casco, 2019; Johannes, Kussmaul, Münte, & Mangun, 1996; Victor, Conte, Burton, & Nass, 1993). Indeed, the stimuli and procedure used for testing is a critically important consideration (Stuart, McAnally, & Castles, 2001), with critics also arguing that tasks designed to measure the M stream do not sufficiently isolate M function from P function (Skottun, 2000; Skottun, 2015a; Skottun, 2015b), or that the variability of findings may be resolved, at least in part, by accounting for subtypes of dyslexia (Skottun, 2000). Thus, further research addressing these gaps and contentions is warranted, not just from a research perspective, but also to ensure timely clinical uptake of a shift in understanding of potential intervention approaches from a traditionally cognitive, and phonologically-based approach to one that is more attuned to understanding of the cognitive neuroscience underlying the role of visual attention in reading.

1.1.4 Temporal Processing

To date, most of the literature examining M functioning in dyslexic populations via psychophysical measures has focused on the static spatial properties of the M pathway - i.e., low spatial frequency and low contrast properties - rather than its temporal properties. This is despite extensive primate and human research showing that stimuli presented at fast temporal frequencies best isolate the M stream (Bullier, Hupé, James, & Girard, 1996; Klistorner et al., 1997; Merigan & Maunsell, 1990; Schiller, Logothetis, & Charles, 1990). For example, Klistorner et al. (1997) demonstrated a 25- 30 millisecond time difference between the arrival of M type and P type input to V1 in adult humans. While temporal processing manipulations are included in motion coherence tasks and contrast sensitivity measured as a function of moving gratings (Benassi, Simonelli, Giovagnoli, & Bolzani, 2010; Williams, Stuart, Castles, & McAnally, 2003), very few studies have examined the biological limits (i.e., thresholds) of temporal processing in dyslexia. Yet, the deployment of visual attention for accurate spatio-temporal parsing of letter information during reading is reliant on the accurate timing of visual sensory input (i.e., temporal processing; Stein, 2019; Vidyasagar, 2013). As such, this thesis aimed to investigate temporal processing thresholds and their relationship with reading skills in dyslexic and neurotypical children.

1.1.5 Rapid Naming and Eye Movements

The task of rapid automatized naming (RAN) is perhaps the most common rate of processing measure used to investigate dyslexia (McLean et al., 2011). RAN requires the rapid verbal naming of a series of familiar visual stimuli (e.g., letters, numbers, objects), is a strong predictor of reading aloud, and is often significantly slower in those with dyslexia (Al Dahhan, Kirby, Brien, & Munoz, 2016; Denckla & Rudel, 1974). An impairment of RAN is believed to characterize an independent subtype of dyslexia (Wolf & Bowers, 1999), however, there is still little agreement on what underpins RAN or how it relates to reading. Some suggest that RAN comprises a microcosm of the processes also required in reading, including low-level temporal processes (McLean et al., 2011), with others argue that RAN simply reflects speed of phonological processing (for a review, see Kirby, Georgiou, Martinussen, & Parrila, 2010). As such, it is important to identify the processes that underlie rapid naming in order to help elucidate which processes are essential to fluent reading and are impaired in dyslexia (Jones, Ashby, & Branigan, 2013). Eye movements, directed by input from the M stream, provide surrogate measures of the temporo-spatial placement of attention (Casteau & Smith, 2020) and may be useful in clarifying the RAN-reading relationship. In fact, research shows that both children and adult with dyslexia exhibit inefficient and atypical eye movement patterns, requiring longer fixation durations, shorter saccades and more fixations than age-matched typical readers, both during reading and non-reading measures (e.g., antisaccade tasks; Biscaldi, Fischer, & Hartnegg, 2000; Caldani, Gerard, Peyre, & Bucci, 2020; Henry, Van Dyke, & Kuperman, 2018). However, to date, eye movements have rarely been used to explore rapid naming (Ashby, Dix, Bontrager, Dey, & Archer, 2013; Kim, Petscher, & Vorstius, 2019; Rayner, 2009). Therefore, studying eye movements during RAN presents a particularly interesting opportunity to investigate the attentional processes that underlie RAN in order to elucidate the RAN-reading relationship.

1.1.6 Visual Attention Training as an Intervention for Dyslexia

Investigations into the use of dynamic visual attention training as novel treatments for dyslexia have gained prevalence in recent years (Facoetti, Lorusso, Paganoni, Umiltà, & Mascetti, 2003; Franceschini et al., 2013; Lawton, 2007). Such research aims to provide unequivocal support for a causal role of attentional and MD deficits in the cognitive neuroscientific understanding of dyslexia, by demonstrating that neuroanatomically based visuo-attentional interventions improve reading ability, despite not directly training traditionally defined reading skills (Franceschini et al., 2013). Moreover, regardless of one's theoretical perspective, one of the most clinically important challenges for researchers lies in the development of successful intervention strategies. The heterogeneity of dyslexia necessitates the development of different approaches to interventions to enable personalized treatment planning based on an individual's profile of deficits. For example, there is evidence to suggest that speed-based reading skills, reliant on temporal processing, are typically resistant to current remediation options but may benefit from the use of action video games as a method of visual attentional training (Franceschini et al., 2017). However, the use of visual attentional interventions is still in the early stages of research and more work is needed. Thus, to address some of these gaps, a systematic review was conducted to identify and synthesize the literature on visual attention interventions for dyslexia and undertook a randomized controlled trial of action video game training.

1.2 Rationale and Aim

The research conducted in this thesis aims to address several diverse gaps in the literature pertaining to visual attention and magnocellular functioning in children with dyslexia, with an emphasis on rate of visual processing and clinically translatable findings. A clear empirical understanding of the role that visual attentional mechanisms play in reading and dyslexia is imperative for the development of novel and effective interventions. Specifically, the aims of the research reported in this thesis address the following research questions:

1. What is the efficacy of visual attentional interventions as a treatment for dyslexia as reported in current research?
2. Do children with dyslexia demonstrate an impairment in magnocellular-based temporal processing thresholds as compared with matched neurotypical children and is this difference driven by dyslexic subtypes?
3. How well do eye movements recorded during rapid naming predict rapid naming performance and reading performance in dyslexic and typical readers?
4. What neural mechanisms drive the efficacy of action video game visual attention training on reading skills in children with dyslexia, and can this training effect be enhanced?

1.3 Thesis Outline

Evidence demonstrating that visual attentional interventions improve reading skills offers the strongest support for a causal basis of attentional and MD deficits in dyslexia. However, this is an emerging area of research and a review of the literature has not yet been undertaken. Therefore, Chapter 2 of this thesis comprises a systematic review of computerized visual attentional interventions for reading in typical and dyslexic children. The review aims to synthesize the existing literature and determine the efficacy of visual attentional interventions as a treatment for dyslexia. Chapter 2 is published as 'Efficacy of Dynamic Visuo-Attentional Interventions for Reading in Dyslexic and Neurotypical Children', in Neuroscience and Biobehavioral Reviews (Peters, De Losa, Bavin, & Crewther, 2019) and has been cited 17 times as of 17th December 2020. Chapters 4 to 6 comprise the experimental chapters for this thesis.

Although M cells are well isolated by high temporal frequency, very few studies have examined the role of temporal processing thresholds in developmental dyslexia. This represents an important unknown in the literature, as many dyslexics experience impaired speed of processing and remain slow dysfluent readers even following intervention (Lefly & Pennington, 1991; Rutkowski et al., 2003). Therefore, Chapter 4 aimed to determine whether children with dyslexia may be characterized by temporal processing impairments indicative of M dysfunction. The study examined the achromatic temporal processing thresholds of dyslexic children and neurotypical children using low and high contrast flicker fusion threshold tasks designed to specifically activate M cells (Brown, Corner, Crewther, & Crewther, 2018). Another aim was to establish the utility of flicker fusion tasks as a potential clinical measure of dyslexia. Chapter 4: Flicker Fusion Thresholds as a Clinical

Identifier of a Magnocellular-Deficit Dyslexic Subgroup, is published in Nature Scientific Reports (Peters, Bavin, Brown, Crewther, & Crewther, 2020).

The similarities between RAN and the task of reading out loud are widely accepted, with both tasks requiring rapid visual attention, recognition and then access to semantic translations, i.e., visual-to-verbal processing (Norton & Wolf, 2012). However, the processes involved in RAN and its association with reading have not been completely elucidated (Kirby et al., 2010) and additional insights may be provided by studying the pattern of eye movements during rapid naming, which reflect the temporo-spatial placement of attention. Thus, the investigation reported in Chapter 5 considered whether the patterns of eye movements predict RAN scores and reading scores, differentiate dyslexic and neurotypical children, and can help to elucidate the relationship of RAN to reading. Chapter 5: Eye Movements during RAN as an Operationalization of the RAN-Reading Microcosm, is published in Frontiers in Human Neuroscience (Peters, Bavin, & Crewther, 2020).

Chapter 6 of this thesis comprises a randomized controlled trial of dynamic visual attentional training in dyslexic children using Action Video Games. The chapter builds on the findings of Chapter 2 and investigates whether increasing the attentional demands of an AVG, by increasing the reliance on precise and organized eye movements, enhances the efficacy of AVG training. The trial also examines a different type of action game with a shorter training duration. Chapter 6 has been submitted for publication consideration as ‘Action Video Game Training Improves Text Reading Accuracy, Rate and Comprehension in Children with Dyslexia: A Randomized Controlled Trial’.

The final chapter, Chapter 7, provides a general discussion of the key findings of the research reported in the thesis, and highlights the importance of the experiments conducted in understanding the role that visual attention plays in reading and its association with dyslexia. Limitations associated with each study are discussed, and suggestions provided for future research directions in order to expand on the research conducted and add to our understanding of dyslexia.

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CHAPTER 2

Efficacy of Dynamic Visuo-Attentional Interventions for Reading in Dyslexic and Neurotypical Children: A Systematic Review

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The published version and the supplementary information for this paper are provided in Appendix F and G, respectively.

2.1 Abstract

Dyslexia is associated with phonological and visuo-attentional deficits. Phonological interventions improve word accuracy and letter-sound knowledge, but not reading fluency. This systematic review evaluated the effectiveness of dynamic computerized visuo-attentional interventions aimed at improving reading for dyslexic and neurotypical children aged 5-15. Literature searches in Medline, PsycINFO, EMBASE, Scopus, ERIC, PubMed, Web of Science, and Cochrane Library identified 1266 unique articles, of which 18 met inclusion criteria (620 participants; 91.40% dyslexic). Three types of visuo-attentional interventions were identified. Results show that visual perceptual training (*n*=5) benefited reading fluency and comprehension, visually-based reading acceleration programs (*n*=8) improved reading accuracy and rate, and action video games (*n*=5) increased rate and fluency. Visuo-attentional interventions are effective options for treating childhood dyslexia, improving reading generally equal to or greater than other strategies. Initial evidence indicates that visuo-attentional interventions may be efficacious in different orthographies, and improve reading for at least two months after intervention. Larger sample interventions on a wider range of reading skills with follow-up assessment are needed to further clarify their effectiveness.

2.2 Introduction

Developmental Dyslexia (DD) is a neurodevelopmental disorder characterised by problems in learning to read and affects 10% of the population worldwide (American Psychiatric Association., 2013). Individuals with DD experience deficits in their ability to decode letters and sounds, and show impaired accuracy and word recognition, consequentially resulting in significant educational and occupational disadvantage throughout the lifespan (Lyon, Shaywitz, & Shaywitz, 2003) despite adequate intelligence and education.

Substantial research over the last fifty years has demonstrated that deficits in reading are associated with both phonological processing (Snowling, 2001; Vellutino, 1979, 1987; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Wagner & Torgesen, 1987; Wagner, Torgesen, & Rashotte, 1994) and visuo-attentional mechanisms in children and adults with DD (Badcock, Hogben, & Fletcher, 2008; Barnard, Crewther, & Crewther, 1996, 1998; Crewther, Crewther, & Klistorner, 1999; Facoetti & Molteni, 2001; Gori, Seitz, Ronconi, Franceschini, & Facoetti, 2016; Lovegrove, Bowling, Badcock, & Blackwood, 1980; Lovegrove & Brown, 1978; Rutkowski, Crewther, & Crewther, 2003; Stein, 2001, 2003, 2018; Stein, Riddell, & Fowler, 1988; Stein & Walsh, 1997), highlighting that DD is a multifaceted, heterogeneous disorder (Menghini et al., 2010).

Since Vellutino (1979), remediation programs focusing on improving phonological processing, known to be one of the strongest predictors of word reading accuracy (Mann & Wimmer, 2002), have been frequently used. Although recent research indicates that such programs are ineffective in up to one third of children (Whiteley, Smith, & Connors, 2007), and when successful, reading outcomes are often in terms of single word and pseudoword reading accuracy and letter-sound knowledge, rather than text reading fluency (i.e., the ability to read text rapidly, accurately, and with prosody) and comprehension (see meta-analyses by Bus, 1999; McArthur et al., 2012). Furthermore, these remediation strategies are resource-demanding, are more beneficial for those learning to read rather than more established readers, and typically reduce the degree of reading difficulty rather than normalize it (Gabrieli, 2009). More recent evidence from children with DD (aged 6-8 years) also shows that around 38 - 53% do not present with phonological deficits (O'Brien, Wolf, & Levett, 2012), necessitating investigations into alternate remediation options.

More recently, research in the area of reading remediation has shifted in emphasis to multiple investigations of non-phonological reading interventions which target visuo-attentional deficits and visuo-attentional mechanisms. Such remediation programs are based on literature showing that spatially and temporally dependent processes, such as dynamic visuo-attention, rapid naming/word recognition, and eye movements, are most predictive of reading rate and fluency (Al Dahhan et al., 2014; Elhassan, Crewther, & Bavin, 2017; Elhassan, Crewther, Bavin, & Crewther, 2015; Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012; Georgiou, Parrila, & Papadopoulos, 2008; Poulsen, Juul, & Elbro, 2015). Thus, visuo-attentional interventions may address the limitations of current dyslexia interventions by targeting other reading skills, such as rate and fluency (e.g., Franceschini et al., 2013). Such remediation evidence would provide further validation that visuo-attentional deficits are contributing factors of DD (Facoetti, Lorusso, Paganoni, Umiltà, & Mascetti, 2003; Franceschini et al., 2012; Franceschini et al., 2013; Gori et al., 2016). Therefore, a thorough review of the current state of research into these types of visuo-attentional interventions for reading is timely and necessary.

2.2.1 Visuo-Attentional Deficits in Dyslexia

Research into DD has reliably identified impairments across visuo-attentional mechanisms. The orienting and focusing of **visuospatial attention,** often described as the 'spotlight of attention', is impaired in dyslexia and results in inefficiencies in selectively extracting and processing the spatial relationship of visual information from a specific region of space within the visual field (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000b; Treisman, 1988). Such individuals demonstrate a more distributed/diffused mode of attention, and are impaired on tasks of focused spatial attention, visual search and visual (peripheral) cuing (Facoetti et al., 2003; Facoetti, Paganoni, & Lorusso, 2000a; Facoetti et al., 2000b; Franceschini et al., 2012; Liu, Liu, Pan, & Xu, 2018; Pammer, Lavis, Hansen, & Cornelissen, 2004; Vidyasagar & Pammer, 2010). Those with DD also demonstrate impairments in the rapid engagement of attention, referred to as '**sluggish attentional shifting**', which results in abnormal temporal, crowding and lateral masking performances, and can be used to predict poor reading outcomes in young children (Facoetti et al., 2010; Franceschini et al., 2018; Hari & Renvall, 2001). Interestingly, considerable evidence indicates that deficits in temporal processing and attention shifting are not exclusive to the visual modality, but are found for transient auditory and cross-modal information (Auditory timing deficits are beyond the purpose of this review, but see Au & Lovegrove, 2001; Casini, Pech-Georgel, & Ziegler, 2018; Stein, 2018).

Individuals with DD, including pre-reading children at risk of DD, demonstrate deficits in **visual motion perception.** This results in reduced proficiency to infer the speed and direction of elements of visual stimuli on tasks such as motion coherence and direction discrimination (Albright & Stoner, 1995; Boets, Vandermosten, Cornelissen, Wouters, & Ghesquière, 2011; Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Gori & Facoetti, 2014; Gori et al., 2016; Kevan & Pammer, 2009; Mascheretti et al., 2018; Stein, 2014). Similarly, dyslexics show **visual temporal processing impairments**, displaying higher gap-detection thresholds to visual stimuli presented sequentially and rapidly (Au & Lovegrove, 2001; Martos & Marmolejo, 1993; Wang & Yang, 2018), longer visual persistence to low-spatial-frequency stimuli, such as measured by contrast sensitivity tasks (Slaghuis & Lovegrove, 1985), as well as slower recognition and correct visual sequencing of letters (Ozernov-Palchik et al., 2017; Stein & Walsh, 1997). Inefficiencies in attentionally-driven **eye movements** are also often evident in those with DD during both reading and non-reading tasks (Al Dahhan et al., 2014; Al Dahhan, Kirby, Brien, & Munoz, 2016; Biscaldi, Fischer, & Hartnegg, 2000; Rayner, Ardoin, & Binder, 2013; Stein & Fowler, 1981). Many dyslexic readers also experience **visuoperceptual anomalies** - displacing and inverting letters within a word, causing words to appear moving, distorted, crowded, or overlapping (Boets, Wouters, van Wieringen, & Ghesquiere, 2007; Facoetti et al., 2003).

What is imperative to all these attentional mechanisms is the dynamic, transient processing of rapidly presented visual information. Unequivocally, when reading text one must sequentially, spatially and temporally select the word to be read; successively and rapidly moving the eye and the attentional spotlight (Laycock & Crewther, 2008). These processes are often linked to the faster subcortical **magnocellular (M) stream** that is responsive to high temporal and low spatial frequencies and responsible for stabilizing and directing eye movements, multisensory selective attention, and motion processing (Bruce, Goldberg, Bushnell, & Stanton, 1985; Stein, 2001, 2003, 2018; Stein & Walsh, 1997). Therefore, the deficits that those with DD show on these tasks are thought to be attributed to an underlying sensitivity weakness of the transient M system, specifically of the **dorsal stream** (Crewther, Crewther, Barnard, & Klistorner, 1996; Gori & Facoetti, 2014; Laycock, Crewther, & Crewther, 2012; Stein, 2001, 2018; Stein & Walsh, 1997; Vidyasagar & Pammer, 2010). In contrast, those with DD do not show impairments in static visuo-attention (Barnard et al., 1998; Hansen, Stein, Orde, Winter, & Talcott, 2001; Lovegrove et al., 1982). Thus, not unexpectedly, past interventions that have focussed on static visuo-attention have not been effective (see Kavale, 1984).

2.2.2 Can Dynamic Visuo-Attention Interventions Improve Reading?

In order for interventions to adequately remediate the dynamic visuo-attention impairments found in DD, maximal loading of spatial and/or temporal processing of visual information, appropriate to the ability of the individual, would be necessary. This would only be feasible through computerised delivery. In fact, there have been several recent reports on improving reading through the use of computerized visual programs that heavily engage spatial and/or temporal attention, including action video games and direction discrimination training, and these have demonstrated success (Franceschini et al., 2013; Lawton, 2004). Importantly, they are examples of active interventions (as opposed to passive interventions) that aim to achieve ongoing cognitive improvement. While existing visuo-attentional intervention studies appear to vary widely in terms of population age (i.e., pre-readers through to adults), the majority have focused on primary school aged children up to age 14 or 15 years (e.g., Facoetti et al., 2003; Gori et al., 2016; Lorusso, Facoetti, & Bakker, 2011). This age range is when intervention is potentially of greatest benefit as children are undergoing rapid neural and developmental periods and attention networks are still maturing (Crewther et al., 1996; Klaver, Marcar, & Martin, 2011; Kolb, 2009; Langrová, Kuba, Kremláček, Kubová, & Vit, 2006; McIntosh, Horner, Chard, Boland, & Good, 2006).

While a number of papers have reported on the usefulness of similar types of interventions for reading in unselected populations or other clinical populations (e.g., Dodick et al., 2017; Kirk, Gray, Ellis, Taffe, & Cornish, 2017), this review is specific to studies of dyslexic children compared to typically developing readers. This criterion was set to establish the role of visuo-attention and efficacy of its intervention in DD.

Thus, the objective of this systematic review is to evaluate the efficacy of active, computerized visuo-attentional interventions that do not include any direct phonological input on the reading of typical and dyslexic children aged 5 to 15 years. Five years is the age when formal education usually begins and when reading can start to be typically assessed and so it is appropriate to start there. Reporting of the systematic review followed PRISMA guidelines (see supplementary document Table S1 for PRISMA checklist; Moher, Liberati, Tetzlaff, Altman, & The Prisma Group, 2009). Table 1 provides a list of abbreviations used throughout the text of the review; those used in a specific table are identified below the table.

Table 1. *Abbreviations*

DD	Developmental Dyslexia
M stream/system	Magnocellular stream/system
ROBINS-I	Risk of Bias in Non-randomised Studies of Interventions
AVG	Action Video Game
Non-AVG	Non-action video games
RAP	Reading Acceleration Program
VPT	Visual Perceptual Training
VHSS	Visual Hemispheric Specific Stimulation
DDT	Direction Discrimination Training
TDT	Texture Discrimination Training
SMD	Standard mean difference
eSMD	Estimate Standard mean difference

2.3 Method

2.3.1 Search Strategy

Prior to performing the review, a complete protocol was pre-specified and registered at PROSPERO (registration number CRD42017060282; Initial registration dated 27/03/2017; Peters, De Losa, Bavin, & Crewther, 2017).

Studies were identified through electronic database searching in Medline (Ovid, 1946 to present), PsycINFO (Ovid, 1806 to present), EMBASE (Ovid), and adapted for Scopus (Elsevier), ERIC (Proquest), PubMed, Web of Science (ISI), and Cochrane Library, for all available years. The final database search was run on 28 August 2018. In addition, hand searching (‘Snowballing’) was also conducted from the reference lists of those studies that met inclusion criteria.

The following search strategy was conducted in MEDLINE (OVID) using MeSH terms and Keywords:

1. (visual or visuo* or vision or attention* or perceptual or eye movement* or fixation* or saccad* or computer or video) adj4 (game* or gaming or treatment or therap* or train* or program* or intervention* or exercis* or remediat*).mp

1. (visual or visuo* or vision or attention* or perceptual or eye movement* or fixation* or saccad* or computer or video) adj4 (game* or gaming or treatment or therap* or train* or program* or intervention* or exercis* or remediat*).mp
2. Video Games/
3. 1 or 2
4. Dyslexia/
5. Dyslexi*.mp
6. (Reading or learning) adj3 (disorder* or disabilit* or difficulty or difficulties or impairment).mp
7. (reader* or reading).mp
8. 4 or 5 or 6
9. 7 and 8
10. 3 and 9

2.3.2 Study Selection

All studies investigating active computerized interventions which target dynamic visuo-attentional processes to improve reading in children aged 5 to 15 years were included in the current review. This included, but was not limited to, interventions targeting visuo- attention/processing/perception, or attentionally-driven eye movements. Further, only neurotypical readers and those with developmental dyslexia were included. Studies that included a ‘dyslexic’ population were required to provide sufficient information to substantiate that participants met criteria for dyslexia. That is, only studies explicitly identifying children as having clinical dyslexia (or an appropriate alternative terminology, i.e., specific learning disorder in reading, reading disorder), that provided the diagnostic criteria employed (e.g., DSM-5, ICD-10, documented diagnosis, reading ability >2 *SD* below age norms), and indicated that all other diagnoses had been excluded. Information about the diagnostic criteria employed by each study is displayed in Table 4. Studies that included typically developing children were similarly required to indicate that all other diagnoses were screened and excluded. Therefore, studies that did not explicitly exclude children with neurological, neurodevelopmental, or uncorrected visual disorders, other than dyslexia, or separately group them (to permit data extraction of relevant group information) were excluded. Studies were included if they measured one or more of the following reading outcomes at either a word or text level - reading rate, accuracy, comprehension, and/or fluency. Further, studies were excluded if they did not separately analyse the efficacy of computerised visuo-attentional training when included in a broader intervention that actively trained other skills (e.g., working memory training); or if they did not include a control or comparison group. Included studies were required to be quantitative and published in English. Case studies and qualitative studies were excluded. There was no limit placed on year of publication.

The eligibility assessment process was performed independently by two reviewers (JP and LD) using the data management service, Covidence (Veritas Health Innovation). The reviewers first independently screened the title and abstract of each identified record to determine whether to accept or reject the study for further review. The reviewers then independently reviewed the method and results section of each potentially relevant study to determine whether to accept or reject the study based on the pre-specified inclusion/exclusion criteria. Disagreements at each stage were settled by a co-author (SC). Where the full-text of a study was not available, contact with the corresponding author was attempted though email. The decision to reject a study was recorded using a custom hierarchy of 8 exclusion reasons:

1. Not written in English
2. Not an intervention study
3. Study design did not meet criteria (Study was qualitative, a case study, or did not include a control/comparison group)
4. Population did not meet criteria (Study did not include a dyslexic and/or typical population aged 5-15 years)
5. Intervention did not meet criteria (intervention was not dynamic, computerised, and/or visuo-attention-based)
6. Outcomes of interest not measured (Study did not measure reading outcomes)
7. Not enough information provided (e.g., published conference presentations)
8. Study did not satisfy risk of bias criteria (see section 2.3.4)

Potentially relevant studies were excluded if the full-text could not be located, or if there was insufficient information to determine if the study met all inclusion criteria and contact with the corresponding author was unsuccessful or the author was unable to provide the requested information. A list of visuo-attentional intervention studies that did not meet the strict inclusion criteria (e.g., population age, other diagnoses not excluded) but are relevant to the area of visuo-attentional interventions has been provided in the supplementary document (See Table S3).

2.3.3 Data Collection Process

A data extraction template was created through Covidence (Veritas Health Innovation). The template was pilot-tested and refined as needed. Each reviewer extracted data on half of the included studies, with the other reviewer checking the extracted data.

1. Study information (country, language, date of study, setting)
2. Participant information (total number, diagnostic criteria, age)
3. Intervention (intervention groups, number of participants allocated to each intervention, intervention description, intervention duration)
4. Outcomes (outcomes and time points, outcome definition, unit of measurement)
5. Results (missing participants, summary data for each intervention group [mean and *SD*s, standard mean difference of change, *p*-value])
6. Miscellaneous (key results and conclusions provided by the study authors)

As data were extracted, a uniformity of terms was applied to the outcome measures so as to allow easier comparisons. For example, the term reading rate was applied for all measures of speed of reading, reading fluency was used for any measure that combined accuracy and speed of reading, and whether reading measures were at a word or text level were delineated. If an included study had missing data (i.e., standard mean difference of change; SMD), contact was attempted with the corresponding author. Where the SMD was not reported or not provided by the author upon request, an estimate of the SMD was calculated, where possible, using guidelines reported in chapter 7.7 of the Cochrane Handbook for Systematic Reviews of Interventions Version 5.1.0 (Higgins & Green, 2011).

2.3.4 Risk of Bias in Individual Studies

Quality assessment of included randomized studies utilized the Cochrane Collaboration's Tool for Assessing Risk of Bias (chapter 8.5) reported in the Cochrane Handbook for Systematic Reviews of Interventions (Higgins & Green, 2011). The Risk of Bias in Non-randomised Studies-of Interventions (ROBINS-I) assessment tool was used as the quality assessment of included non-randomised studies (Sterne et al., 2016). Assessments were completed at the study level and were conducted independently by two reviewers (JP and LD). Where the two reviewers disagreed on the level of risk for a domain, a co-author (SC) was consulted to determine the appropriate risk of bias level. Where insufficient information was available to assess the risk of bias for a domain, the corresponding authors were contacted for further information.

As the two Risk of Bias tools used had distinct criteria, the decision to exclude studies of insufficient quality needed to be based on domains comparable across the tools and study designs. Therefore, studies were excluded if they displayed High/Critical (Cochrane/ROBINS-I respectively) levels of risk for their intervention/group descriptions, deviations from interventions, and reporting of results. Intervention/group description and deviations from intervention were assessed under the ROBINS-I ‘classification of interventions’ and ‘deviations from intended interventions’ domain respectively and for Cochrane, under the ‘other sources of bias’ domain, while reporting of results was assessed under the ROBINS-I ‘reported result’ domain and Cochrane ‘selective reporting’ domain. It is important to note that the Risk of Bias assessments apply only to how well study results assessed the outcomes of interest to the current systematic review, irrespective of the objectives of the original study.

2.4. Results

2.4.1 Risk of Bias Within Studies

Risk of bias assessments for the non-randomised (ROBINS-I) and randomised (Cochrane Risk of Bias Assessment) interventions were conducted to ascertain if the studies satisfied the final inclusion criteria (exclusion reason 8) and determine the study quality in relation to the objective of the current review (see Tables 2 and 3). Two non-randomised studies displayed critical risk of bias in each of the ‘classification of interventions’, ‘deviations from intended interventions’ and ‘reported result’ domains when reviewed in line with the objectives of the current review and were therefore excluded from further review (see supplementary document Table S3 for further information; Lawton, 2007, 2011).

Table 2. *ROBINS-I Risk of Bias Assessment for Non-Randomised Trials*

Author	confounding	Selection of Participants	Classification of Intervention	Deviations from Intended interventions	Missing Data	Measurement of Outcomes	Reported Result	Overall
Das-Smaal et al., 1996	Low	Low	Low	Low	Low	Moderate	Moderate	Moderate
Franceschini et al., 2013	Low	Low	Low	Low	Low	Low	Moderate	Moderate
Franceschini et al., 2017a.2	Low	Low	Low	Low	Low	Moderate	Moderate	Moderate
Gori et al., 2016	Low	Low	Low	Low	Low	Serious	Moderate	Serious
Judica et al., 2002	Moderate	Low	Low	Moderate	Low	Moderate	Moderate	Moderate
Lawton 2007	Serious	Low	Critical	Critical	Low	Low	Critical	Critical
Lawton 2008	Moderate	Low	Serious	Low	Low	Moderate	Moderate	Serious
Lawton, 2011	Serious	Critical	Critical	Critical	Low	Serious	Critical	Critical
Luniewska et al., 2018	Moderate	Low	Low	Low	Low	Moderate	Moderate	Moderate
Meng et al., 2014	Moderate	Low	Low	Low	Low	Low	Moderate	Moderate

Note.

- (green) Low Risk of Bias: "comparable to a well-performed randomized trial"
- (yellow) Moderate Risk of Bias: "Sound for a non-randomised study… but cannot be considered comparable to a well-performed randomized trial"
- (orange) Serious Risk of Bias: " The study has some important issues"
- (red) Critical Risk of Bias: "the study is too problematic to provide any useful evidence on the efffects of intervention"
- **?** No Information: Insufficient information provided to determine risk of bias

Overall Risk of Bias: Equivalent to the highest level of bias found in any domain (Sterne et al., 2016).

Table 3. *Cochrane Risk of Bias Assessment for Randomised Trials*

Author	Random Sequence Generation	Allocation Concealment	Blinding of Participants/ Personnel	Blinding of Outcome Assessment	Incomplete Outcome Data	Selective Reporting	Other Sources of Bias	**Overall**
Facoetti et al., 2003	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟢
Franceschini et al., 2017a.4	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢
Franceschini et al.,2017b	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟢
Lawton, 2004	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟢
Lawton, 2016	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🟢
Lawton et al., 2017	🔴	🟡	🔴	🟢	🟢	🔴	🟢	🟢
Lorusso et al., 2004	🔴	🟢	🟢	🟢	🟢	🟡	🟢	🟢
Lorusso et al., 2005	🔴	🟢	🟢	🟢	🟢	🟡	🟢	🟢
Lorusso et al., 2006	🔴	🟢	🟢	🟢	🟢	🟡	🟢	🟢
Lorusso et al., 2011	🔴	🟢	🟢	🟢	🟢	🟡	🟢	🟢

Note.

🟢 Low Risk of Bias

🟡 Unclear Risk of Bias: Insufficient information provided to determine risk of bias

🔴 High Risk of Bias

Overall Risk of Bias: Equivalent to the highest level of bias found in the blinding domains. These domains were identified as the most important to the aims and purpose of the current review given their impact on the other risk of bias domains (Higgins & Green, 2011).

2.4.2 Study Selection

Database and hand searching identified a total of 2309 citations, of which 1266 were unique citations (duplicates n = 1043). Following title and abstract screening, 252 were identified as eligible for full-text review, while 1014 were removed as they clearly did not meet inclusion criteria. Full-text review of the remaining articles excluded 232 that did not meet inclusion criteria. Eight were not written in English; 42 were not intervention studies; the study design of 3 did not meet criteria; the populations studies in 36 did not meet criteria; the interventions of 125 did not meet criteria; 6 did not measure the primary outcomes; 12 did not provide enough information (e.g., conference abstracts); and 2 did not satisfy risk of bias criteria. A total of 17 articles, involving 18 studies, were identified for inclusion in the systematic review (Figure 1). The corresponding authors of all included studies were contacted to provide further information for data extraction and/or risk of bias assessment. Of the nine corresponding authors of the 17 included articles and 18 individual studies, seven authors/co-authors responded and six were able to provide some or all further information requested on a total of 16 studies (See Tables S4-17 in the Supplementary Information Document for correspondence and additional information from the authors of included papers).

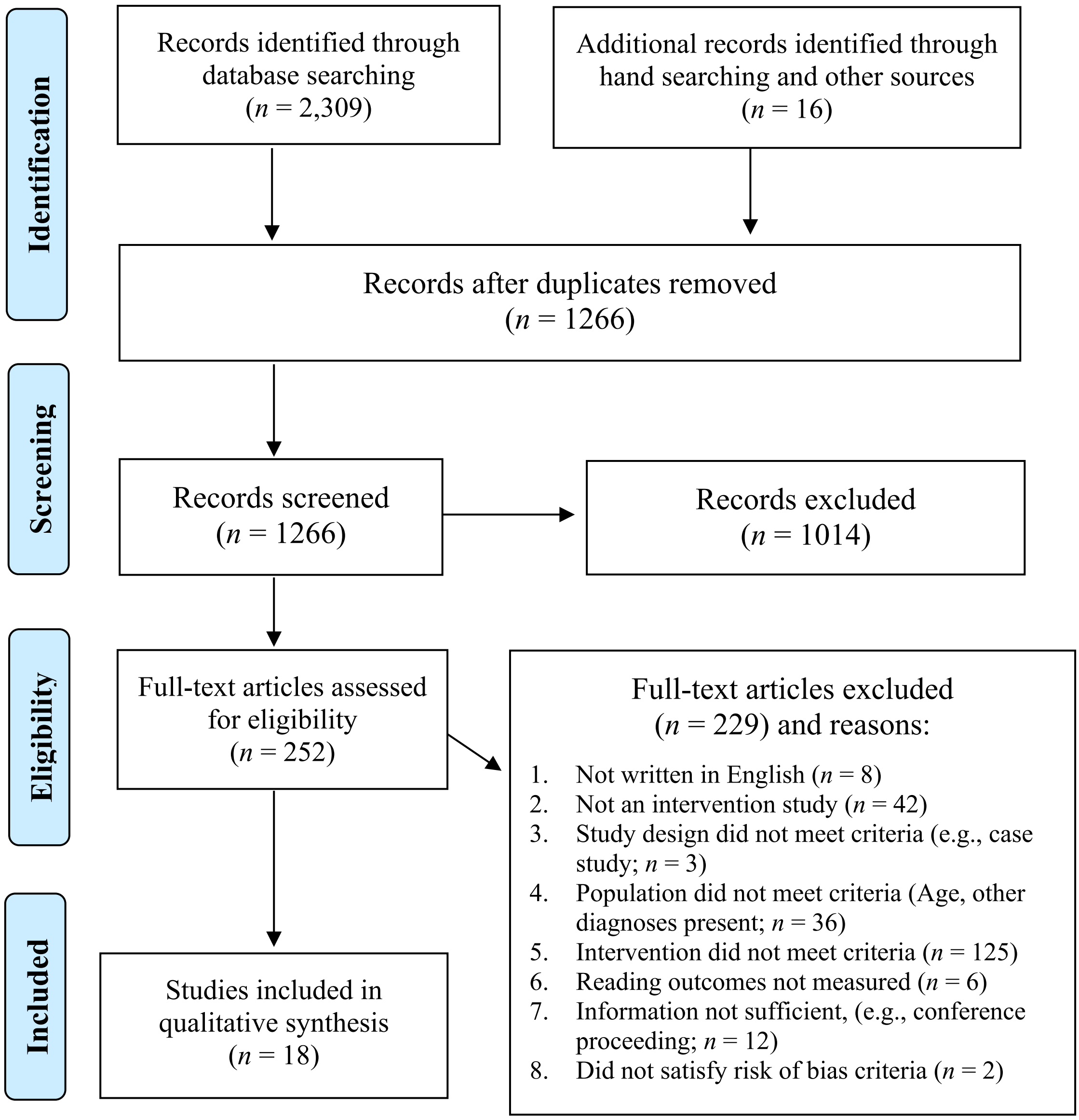

*Figure 1.*PRISMA Flow Diagram Depicting how Articles were selected for Review.

2.4.3 Study Characteristics

The included studies were characterised by both non-randomised (44.44%) and randomised (55.56%) interventions. The studies involved a total of 620 participants, the majority diagnosed with DD (91.40%). Variants of a total of seven visuo-attentional interventions covering three main types – referred to here as action video games (AVGs; *n* = 5), reading acceleration programs (RAPs; *n* = 8), and visual perceptual training (VPT; *n* = 5) – were included and compared against control treatments (38.80%), no treatment (27.70%), and comparison treatments or groups (55.50%). Of the primary reading outcomes, 66.67% of studies assessed text/word reading accuracy, 61.11% assessed text/word reading rate, 50% assessed text/word reading fluency, and 27.78% assessed reading comprehension. Although not the focus of the current review, many of the included studies also assessed non-reading outcomes, such as phonological awareness (50%), pseudoword decoding (66.67%), visuo-attentional processes (61.11%), short-term working and long-term memory (27.78%), and spelling (22.22%) (See supplementary document Table S2 for further information). Study characteristics are presented in Table 4 and include any additional information provided by study authors. Additional information collected mainly pertained to information on location of study, blinding of participants/personnel/ outcome assessors, pre/post-test period, age ranges, and SMD.

Table 4. *Characteristics of Included Studies*

				Participants			Intervention Details			Aims Concealed?	
#	Citation	Language	Study Design	*N*	Age *M* (*SD*); Range	Diagnostic Criteria	Intervention	Administration/ Location	Skills Assessed (Tests Used)	Participants	Assessors
1	Das-Smaal et al., 1996	Dutch	NRCT	*N* = 33 with Dyslexia	9.68; 9 - 10	Reading > 2 years below age norms; 'average intelligence' Further classified into Bakker's subtypes	Multi-letter Reading Acceleration Program Vs Maths and Finger Exercises (Control)	Group; School	• **Word reading accuracy, rate and fluency** (Word and Flashword Tasks*) • Pseudoword decoding accuracy, rate and fluency (Word and Flashword Tasks*) • Multi-letter unit identification (Unit Detection Task*)	N/A	N
2	Facoetti et al., 2003	Italian	RCT	*N* = 24 with Dyslexia	9.84; 7 - 9	DSM-IV (reading ≥2*SD* below age norms); IQ ≥ 85 Further classified into Bakker's subtypes	VHSS Vs Standard Reading Treatment (Comparison)	Individual; Hospital	• **Text Reading accuracy, rate and fluency** (La verifica dell'apprendimento della lettura) • Covert visual attention orienting*	Y	Y
3	Franceschini et al., 2013	Italian	NRCT	*N* = 20 with Dyslexia	9.84 (1.43); 8 - 11	DSM-IV (reading ≥2*SD* below age norms); IQ ≥ 85	AVG Vs NAVG (Control)	Individual; Hospital	• **Text reading accuracy and rate** (MT) • Pseudoword decoding list accuracy and rate (DDE) • Pseudoword decoding list accuracy and rate * • Pseudoword text accuracy and rate* • Phonological awareness - syllabic blending* • Focused and distributed visual spatial attention* • Cross-modal attention*	Y	Y

4	Franceschini et al., 2017a Experiment 2	Italian	NRCT - crossover	*N* = 13 with Dyslexia	10.17 (1.87); 8 - 14	DSM-5 (reading ≥1.5 *SD* below age norms); IQ ≥ 85	'The Library Tower' Reading Acceleration Program Vs No Treatment	Individual; Rehabilitation Centre	• **Text reading accuracy and rate** (DDE) • Pseudoword decoding accuracy and rate (Batteria De.Co.Ne. per la lettura) • Phonological awareness - pseudoword repetition (VAUMeLF) • Navon multiple stimuli naming task*	Y	N
5	Franceschini et al., 2017a Experiment 4	Italian	RCT	*N* = 14 with Dyslexia	10.41 (1.71); 8 - 14	DSM-5 (reading ≥1.5 *SD* below age norms); IQ ≥ 85	AVG Vs NAVG (Control)	Individual; Clinical Centre	• **Text reading accuracy and rate** (DDE) • Pseudoword decoding accuracy and rate* • Navon task*	Y	Y
6	Franceschini et al., 2017b	English (Aus)	RCT	*N*=28 with Dyslexia	10.10; 7.8 - 14.3	Documented diagnosis; IQ ≥ 85	AVG Vs NAVG (Control)	Individual; University	• **Word reading accuracy and rate** (TOWRE-2) • Pseudoword decoding accuracy and rate (TOWRE-2) • Auditory-phonological working memory - short-term memory for trigrams and phoneme blending tasks* • Focused and distributed visual spatial attention* • Visual, auditory, and visual-auditory processing* • Cross-sensory attention shifting*	Y	Y
7	Gori et al., 2016 Experiment 3	Italian	NRCT, crossover	*N* = 11 with Dyslexia	11.02 (1.26); 9.9 - 12.9	DSM-5 (reading ≥2*SD* below age norms); IQ ≥ 85	AVG Vs NAVG (Control)	N/A	• **Text reading fluency** (ratio between accuracy and rate; DDE) • Pseudoword decoding fluency* • Phonological awareness - Pseudoword repetition (VAUMeLF) • Coherent dot motion task* • Illusory motion task* • Parvocellular-ventral task*	Y	N/A
8	Judica et al., 2002	Italian	NRCT	*N* = 18 with Dyslexia	11.83 (0.63); 11 - 12	Reading accuracy and/or rate ≥1.65 *SD* below age norms on two	'Tachistoscopio' Reading Acceleration Program Vs No Treatment	Individual; School	• **Text reading accuracy, rate and comprehension** (MT) • **Word reading accuracy and rate (DDD)**	N	N

						reading tests; IQ ≥ 80			• Pseudoword decoding accuracy and rate, homophonic word correction, lexical decision accuracy and rate (DDD) • Eye movements during reading* • Vocal reaction times during reading*		
9	Lawton, 2004	English (USA)	RCT	*N* = 33 with Dyslexia	7.3 (0.5); 6.1 - 8.2	Identified using the Dyslexia Determination Test; 'normal intelligence'	'Moving to Read' DDT Vs Word Discrimination (Control) Vs No Treatment	Group; School	• **Reading comprehension** (GSRT) • **Computerised reading fluency test*** • **Reading grade level** (Dyslexia Determination Test) • **Word reading accuracy** and spelling (WRAT3) • Processing speed (WISC)	Y	Y
10	Lawton, 2008	English (USA)	NRCT	*N* = 30 15 Typically Developing 15 with Dyslexia	7.0 (0.5); 5 - 9	Identified using The Dyslexia Screener; 'normal intelligence'	'PATH to Reading' DDT	Individual; School	• **Computerised reading fluency test*** • Filtered text reading rate* • Reading fluency across treatment frequency	N	Y
11	Lawton, 2016	English (USA)	RCT	*N* = 58 with Dyslexia	7.40 (0.40); 7-8	Identified using the DESD	'PATH to Reading' DDT Vs FastForWord (Comparison) Vs Linguistic Word Building (Control)	Both Individual and Group; School	• **Computerised reading fluency test*** • **Reading comprehension** (GORT) • Phonological awareness – Blending words subtest(CTOPP) • Attention (CAS) • Sequential and nonsequential visual and auditory working memory, and delayed recall (TIPS) • Direction discrimination*	Y	Y

12	Lawton & Shelley-Tremblay, 2017	English (USA)	RCT	*N* = 42 20 Typically Developing 22 with Dyslexia	8.5 (0.5); 7.6 – 9.7	Identified using the Dyslexia Determination Test	'PATH to Reading' DDT Vs 'Raz-Kids' Guided Reading (Comparison)	Group; School	• **Computerised reading fluency test*** • **Text reading comprehension** (GORT-5) • Phonological awareness – Blending word subtest (CTOPP) • Attention – Stroop and number detection subtests(CAS) • Sequential and non-sequential visual and auditory working memory, and delayed recall (TIPS)	N	Y
13	Lorusso et al., 2004	Italian	RCT	*N* = 30 with Dyslexia	10.35 (1.76); 7 - 14	ICD-10 (reading ≥2*SD* below age norms); IQ > 85	Various manipulations of 'Flash Word' VHSS	Individual; Outpatient Clinic	• **Text reading accuracy and rate** (MT) • **Word reading accuracy and rate** (DDE) • Pseudoword decoding accuracy and rate, spelling (DDE)	Y	Y
14	Lorusso et al., 2005	Italian	RCT	*N* = 12 with Dyslexia	8 - 14	ICD-10 (reading ≥2*SD* below age norms); IQ > 85 Further classified into Bakker's subtypes	Standard Lateral 'Flash Word' VHSS Vs Random Lateral 'Flash Word' VHSS	Individual; Hospital	• **Word reading accuracy and rate** (DDE) • Pseudoword decoding accuracy and rate (DDE) • Visual spatial attention – Form resolving field*	Y	Y
15	Lorusso et al., 2006	Italian	RCT	*N* = 25 with Dyslexia	9.84 (2.19); 7 - 15	ICD-10 (reading ≥2*SD* below age norms); IQ > 85 Further classified into Bakker's subtypes	Standard Lateral 'Flash Word' VHSS Vs Standard Reading Treatment (Comparison)	Individual; Outpatient Clinic	• **Text reading accuracy and rate** (MT) • **Word reading accuracy and rate** (DDE) • Pseudoword decoding accuracy and rate, spelling (DDE) • Phonological awareness* • Working memory and memory (TEMA)	Y	Y

16	Lorusso et al., 2011	Italian	RCT	*N* = 123 with Dyslexia	10.53 (1.83); 7 - 15	ICD-10 (reading ≥2*SD* below age norms); IQ > 85 Further classified into Bakker's subtypes	Various manipulations of 'Flash Word' VHSS Vs Standard Reading Treatment (Comparison)	Individual; Outpatient Clinic	• **Text reading accuracy and rate** (MT) • **Word reading accuracy and rate** (DDE) • Pseudoword decoding accuracy and rate, spelling (DDE) • Phonological awareness* • Working memory and memory (TEMA)	Y	Y
17	Luniewska et al., 2018	Polish	NRCT	*N* = 70 with Dyslexia	11.25; 8.8 - 14	Documented diagnosis, confirmed with standardized assessment (IQ and reading tests); IQ ≥ 85	AVG Vs Phonological video game (comparison) Vs No Treatment (only completed the web-based outcome tasks)	Both Individual and Group; Research Institute	• **Word reading rate and fluency** (Test Dekodowania) • Pseudoword decoding rate and fluency (Test Dekodowania) • Phoneme deletion (Diagnoza dysleksji u uczniów kl. III szkoły podstawowej) • Vowel replacement task • Pseudoword repetition (Test powtarzania pseudosłów) • Selective attention (IDS Skale Inteligencji) • Rapid naming – objects, colours, numbers, letters (Test Szybkiego Nazywania) • Real word recognition, **sentence reading comprehension**, and pseudoword decoding tasks – Web-based tasks*	N	Y
18	Meng et al., 2014	Chinese	NRCT	*N* = 36 18 Typically Developing 18 with Dyslexia	10.87 (0.76); 8 - 12	1.5 grade level delay in character recognition; below average reading fluency scores; typical IQ.	Texture Discrimination Vs No Treatment	N/A; University	• **Text reading fluency** (The Reading Fluency Test) • Vocabulary – real character recognition (The Standardised Chinese Character Recognition Test) • Texture discrimination task*	N/A	N/A

Note. N/A = Information was not available. **Interventions:** VHSS = Visual Hemispheric Specific Stimulation; AVG = Action Video Game; NAVG = Non-Action Video Game (Control Treatment); DDT = Direction Discrimination Training; Standard Reading Treatment refers to remediation programs commonly used by clinicians for the treatment of dyslexia that target reading sub-skills, such as phonological awareness, and teach guided reading and compensatory strategies; the Phonological Video Game trained phonological skills and did not meet criteria as an action video game; **Skills Assessed:** Bolded text = reading outcomes of interest; * = task is experimental; CAS = Cognitive Assessment Systems test of Expressive Attention; CTOPP = Comprehensive Test of Phonological Processing; DDD = Developmental Dyslexia and Dysorthography battery DDE = Batteria per la Valutazione della Dislessia e della Disortografia Evolutiva; DESD = Decoding Encoding Screener for Dyslexia; GORT = Gray Oral Reading Test; GSRT = Gray Silent Reading Test; MT = MT Reading Test (Test for speed and accuracy in reading, developed by the MT group/Prove di rapidita e correttezza nellalettura del gruppo MT; TEMA = Test di Memoria e Apprendimento; TIPS = Test of Information Processing Skills (TIPS); TOWRE-2 = Test of Word Reading Efficiency 2; VAUMeLF = Batterie per la valutazione dell'attenzione uditiva e della memoria di lavoro fonologica in età evolutiva; WISC = Wechsler Intelligence Scale for Children; WRAT3 = Wide Range Achievement Test 3.

2.4.4 Results of Individual Studies

Information from the included studies are presented in Table 5 with any additional information that has been provided by study authors. For each study, Table 5 summarises the citation, matched group design (if relevant), intervention and group size information, duration of the interventions, pre/post-test period, and the various reading outcome measures, including SMD or estimated SMD where calculation was possible (see supplementary document Table S2 for non-reading outcome information). In line with the aims of this review, any combined outcome measures of reading were separated where possible. Individual outcomes were not able to be separated for three studies which used composite measures of reading that included word, pseudoword, and text reading tasks (Lorusso et al., 2011; Lorusso, Facoetti, & Molteni, 2004; Lorusso, Facoetti, Paganoni, Pezzani, & Molteni, 2006). Additionally, where relevant, only main group outcomes were included for studies that also compared outcome efficacy between sub-types of dyslexia. Main group outcomes were not available for one paper and so results for dyslexic subtypes have been provided (Lorusso et al., 2011). As hypothesised in the pre-specified protocol, heterogeneity of the interventions precluded meta-analysis across the included studies. Six of the 18 studies did not provide sufficient information to be included in a meta-analysis, while several more papers did not include sufficient information for every reading outcome. Further, meta-analysis within the three overarching intervention types that have been identified in the current systematic review was not considered appropriate as interventions within subtypes were still diverse, and studies of the same intervention protocol were predominately by the same groups of authors and therefore susceptible to possible non-independence (Noble, Lagisz, O'dea, &

Nakagawa, 2017). Therefore, it was necessary to conduct a qualitative synthesis to best capture the breadth of research on this topic.

Table 5. *Main Results of Included Studies*

#	Citation	Covariates Matched between Groups	Intervention Group *N* and Description	Intervention Duration	Pre/Post Treatment Test Period	Reading Outcomes (*p*; SMD)
1	Das-Smaal et al., 1996	Age, IQ, Reading	Treatment Group *n* = 17 with DD Multiletter Reading Acceleration Program Active Control Group *n* = 16 with DD Computerized maths and motor finger exercises	30 minute sessions, twice a week for 8 weeks (16 sessions). Total = 8 hours	Within 2 weeks of treatment	Word Reading Accuracy – Both groups improved significantly following treatment, $p < .05$ Word Reading Rate – Neither group improved significantly following treatment, $p < .01$ Word Reading Fluency – The treatment group improved significantly more than controls following treatment, $p < .05$
2	Facoetti et al., 2003	Age, IQ, Reading, Attention	Treatment Group *n* = 12 with DD Standard lateral presentation VHSS Comparison Group *n* = 12 with DD Standard Reading Treatment	45 minute sessions, conducted twice weekly for 4 months (32 sessions). Total = 24 hours	2 - 7 days before and following treatment	Text Reading Accuracy – Only the VHSS group improved significantly following treatment, $p <.02$ Text Reading Rate - Only the VHSS group improved significantly following treatment, $p <.0001$
3	Franceschini et al., 2013	Age, Reading, Phonological Ability	Treatment Group *n* = 10 with DD AVG Active Control Group *n* = 10 with DD NAVG	80 minute sessions, conducted each weekday for 2 weeks (9 sessions). Total = 12 hours	3-5 days before treatment and 1-3 days following treatment	Text Reading Rate – only the AVG group improved significantly following treatment, $p =.02$, SMD = 0.67 Text Reading Accuracy – analyses not provided Text Reading Fluency (ratio between accuracy and rate) – only the AVG group improved significantly following treatment, $p =.03$, SMD = 0.99
4	Franceschini et al., 2017a Experiment 2	Not Applicable	*N* = 13 with DD No Treatment followed by the 'The Library Tower' Reading Acceleration Program	No treatment phase: 2 to 3 week period of no treatment. The Library Tower treatment phase: 40 minute sessions, conducted most days for 2 or 3 weeks (10 sessions). Total = 6 hours, 40 minutes	1 - 3 days before and after each treatment phase	Text Reading Accuracy – Participants did not significantly improve following either treatment phase, $p = .41$, SMD = 0.55 Text Reading Rate – Participants improved significantly only following RAP treatment, $p = .04$, SMD = 0.29 Two months following treatment, participant's had maintained performances for reading accuracy, $p = .16$, and reading rate, $p = .44$.

5	Franceschini et al., 2017a Experiment 4	Reading; Phonological Ability Age differed between groups, p = .001	Treatment Group n = 7 with DD AVG Active Control Group n = 7 with DD NAVG	80 minute sessions, conducted each weekday for 2 weeks (9 sessions). Total = 12 hours	3-5 days before treatment and 1-3 days following treatment	Text Reading Accuracy – Neither the AVG nor NAVG groups improved significantly following treatment, p >.05, SMD = 0.81 Text Reading Rate - Only the AVG group improved significantly following training, p = .032, SMD = 1.21
6	Franceschini et al., 2017b	Age, Reading	Treatment Group n = 16 with DD AVG Active Control Group n = 12 with DD NAVG	80 minute sessions, conducted each weekday for 2 weeks (9 sessions). Total = 12 hours	3-5 days before treatment and 1-3 days following treatment	Word Reading Accuracy - Neither the AVG nor NAVG groups improved significantly following treatment, p > .05 Word Reading Rate – Only the AVG group improved significantly following training, p = .024, SMD = 0.86
7	Gori et al., 2016 Experiment 3	Not applicable	N = 11 with DD NAVG followed by AVG	For each treatment program: 80 minute sessions, conducted each weekday for 2 weeks (9 sessions). Total = 12 hours each	3-5 days before each treatment and 1-3 days following each treatment	Text Reading Fluency (mean of accuracy and rate) – Participants improved significantly only following AVG treatment, p = .013, eSMD = 0.80
8	Judica et al., 2002	Age, IQ, Reading	Treatment Group n = 9 with DD 'Tachistoscopio' Reading Acceleration Program Control Group n = 9 with DD No treatment provided	1 hour sessions, conducted twice weekly for 5 months (35 sessions). Total = 35 hours	Within 1 month before treatments and within 2 weeks following treatment	Text Reading Accuracy – Only the treatment group improved significantly following the treatment period, p < .05, SMD = 0.88 Text Reading Rate – Neither group improved, the control group performed significantly worse following the treatment period, p < .05, SMD = 0.45 Text Reading Comprehension – Both groups performed significantly worse following the treatment period, p < .05 Word Reading Accuracy – Only the treatment group improved significantly following treatment, p < .05, SMD = 0.64 Word Reading Rate – Only the treatment group improved significantly following treatment, p < .05, SMD = 0.38
9	Lawton, 2004	Reading	Treatment Group n = 18 with DD 'Moving to Read' DDT	5-10 minute sessions, conducted twice weekly for	Within 1 week of treatment	Reading Comprehension - The DDT group improved significantly more than the other groups following training, p = .02 • DDT Vs. Word Game, SMD = 1.40

			Active Control Group $n = 9$ with DD Word Discrimination Game Control Group $n = 6$ with DD No Treatment	15 weeks (30 sessions). Total = 2.5 to 5 hours		• DDT Vs No Treatment, SMD = 1.00 Text Reading Fluency – The DDT group improved significantly more than the other groups following training, $p = .0008$ • DDT Vs. Word Game, SMD = 1.80 • DDT Vs. No Treatment, SMD = 1.98 Reading Grade Level - The DDT group improved significantly more than the other groups following training, $p = .006$ • DDT Vs. Word Game, SMD = 1.10 • DDT Vs. No Treatment, SMD = 1.30 Word Reading Accuracy - The DDT group improved significantly more than the other groups following training, $p =.016$ • DDT Vs. Word Game, SMD = 0.50 • DDT Vs. No Treatment, SMD = 0.90
10	Lawton, 2008	Age, Grade Level	Treatment Group $n = 15$ with DD 'PATH to Reading' DDT of between two and six replications Treatment Comparison Group $n = 15$ TD 'PATH to Reading' DDT of between two and six replications	10-15 minute sessions, conducted weekly. For between 2 and 6 replications of treatment. Total = 1 to 3 hours	Within 1 week of treatment	Text Reading Fluency - Both groups improved significantly following treatment, $p <.01$ Text Reading Fluency improved significantly more as frequency of training was increased, $p <.001$
11	Lawton, 2016	Age, Reading, Attention, Working Memory	Treatment Group $n = 26$ with DD 'PATH to Reading' DDT Comparison Group $n = 6$ with DD 'FastForWord' Auditory Timing Treatment Active Control Group $n = 26$ with DD Linguistic Word Building	DDT: 15-30min sessions, conducted 3 days per week, for 20 weeks (60 sessions). Total = 20 to 30 hours FastForWord: 30min sessions, conducted 5 days per week for 20 weeks (100 sessions). Total = 50 hours	Within 1 week of treatment	Reading Fluency – The DDT group improved significantly more than the control group, $p = .0004$, and FastForWord group following training, $p < .001$ • PATH Vs Word Game, estimated SMD = 0.83 • PATH Vs FastForWord, estimated SMD = 1.71 Reading Comprehension - The DDT group improved significantly more than the control group, $p = .046$, but not FastForWord group, which improved significantly more following treatment, $p = 0.0011$ • PATH Vs Word Game, estimated SMD = 0.56

						• PATH Vs FastForWord, estimated SMD = -1.63
12	Lawton & Shelley-Tremblay, 2017	Age, Phonological Ability, Attention, Working Memory Reading was matched between the DD and TD groups respectively	Treatment Group n = 12 with DD 'PATH to Reading' DDT Treatment Group n = 9 TD 'PATH to Reading' DDT Comparison Group n = 10 with DD 'Raz-Kids' Guided Reading Comparison Group n = 11 TD 'Raz-Kids' Guided Reading	DDT = 15 - 20 minute sessions, three times a week for 12 weeks (36 sessions). Total = 9 - 12 hours RazKids= 30 minute sessions, three times a week for 12 weeks (36 sessions). Total = 18 hours	Within 1 week of treatment	Reading fluency - Both DDT groups improved significantly more that the Raz-Kids groups following treatment, p = .006 • TD PATH Vs TD Raz Kids, estimated SMD = 1.29 • DD PATH Vs DD Raz Kids, estimated SMD = 1.23 • DD PATH Vs TD PATH, estimated SMD = -1.27 Reading Comprehension - Both the DDT groups improved significantly more that the Raz-Kids groups following treatment, p = .001 • TD PATH Vs TD Raz Kids, estimated SMD = 1.65 • DD PATH Vs DD Raz Kids, estimated SMD = 1.57 • DD PATH Vs TD PATH, estimated SMD = -1.62
13	Lorusso et al., 2004	Age, IQ, Reading, Sex	Treatment Group n = 9 with DD Standard Lateral (SL) Presentation 'Flash Word' VHSS Treatment Group n = 7 with DD Random Lateral (RL) Presentation 'Flash Word' VHSS Treatment Group n = 8 with DD Central (C) Presentation 'Flash Word' VHSS Treatment Group n = 6 with DD Central Fixed-Time (CFT) 'Flash Word' VHSS	45 minute sessions, conducted twice a week over a 4 month period (32 sessions). Total = 24 hours	4-5 days before and following treatment	Global Reading Accuracy (a composite of text, word and pseudoword reading accuracy tasks) – All groups improved significantly following treatment, p <.001 • SL Vs RL, SMD = 0.01 • SL Vs C, SMD = -0.17 • SL Vs CFT, SMD = -0.32 • RL Vs C, SMD = -0.30 • RL Vs CFT, SMD = -0.45 • C Vs CFT, SMD = -0.15 Global Reading Rate (a composite of text, word and pseudoword reading rate tasks) – All groups improved significantly following treatment, p <.001 • SL Vs RL, SMD = -0.46 • SL Vs C, SMD = -0.12 • SL Vs CFT, SMD = -0.59 • RL Vs C, SMD = 0.34

						• RL Vs CFT, SMD = -0.13 • C Vs CFT, SMD = -0.47
14	Lorusso et al., 2005	Age, Reading	Treatment Group *n* = 6 with DD Standard Lateral Presentation 'Flash Word' VHSS Treatment Group *n* = 6 with DD Random Lateral Presentation 'Flash Word' VHSS	45 minute sessions, conducted twice a week over a 4 month period (32 sessions). Total = 24 hours	Immediately before and following treatment	Word Reading Accuracy – Both groups improved significantly following treatment, p =.019 Word Reading Rate – Both groups improved significantly following treatment, p =.023
15	Lorusso et al., 2006	Age, IQ, Reading, Sex	Treatment Group *n* = 14 with DD Standard Lateral Presentation 'Flash Word' VHSS Comparison Group *n* = 11 DD Standard Reading Treatment	45 minute sessions, conducted twice a week over a 4 month period (32 sessions). Total = 24 hours	Immediately before and following treatment	Global Reading Accuracy (a composite of text, word and pseudoword reading accuracy tasks) – The VHSS Group improved significantly more following treatment, $p <.001$, SMD = 1.32 Global Reading Rate (a composite of text, word and pseudoword reading rate tasks) – All groups improved significantly following treatment, $p = .001$, SMD = -0.04
16	Lorusso et al., 2011	Age, IQ, Reading, Sex	Treatment Group *n* = 33 with DD (5 L-types, 15 P-types, and 13 M-types) Standard Lateral (SL) Presentation 'Flash Word' VHSS Treatment Group *n* = 22 with DD (5 L-types, 4 P-types, and 13 M-types) Random Lateral (RL) Presentation 'Flash Word' VHSS Treatment Group *n* = 18 with DD (2 L-types, 5 P-types, and 11 M-types) Central Presentation (C) 'Flash Word' VHSS Treatment Group *n* = 15 with DD (1 L-types, 7 P-types, and 7 M-types)	45 minute sessions, conducted twice a week over a 4 month period (32 sessions). Total = 24 hours	Immediately before and following treatment	Global Reading Accuracy (a composite of text, word and pseudoword reading accuracy tasks) For the P-type and L-type dyslexics, the SL VHSS group improved significantly more than the CFT and RevL VHSS groups following treatment, but did not differ significantly in improvement from the other groups. • SL Vs Phon, p = 0.11, estimated SMD = 0.77 • RL Vs Phon, p = 0.35, estimated SMD = 0.48 • C Vs Phon, p = 0.23, estimated SMD = 0.59 • CFT Vs Phon, p = 0.49, estimated SMD = -0.34 • RevL Vs Phon, p = 0.58, estimated SMD = -0.27 For the M-type dyslexics, groups did not differ significantly in improvement following treatment, *ps* >.10 • SL Vs SRT, estimated SMD = 0.62 • RL Vs SRT, estimated SMD = 0.56 • C Vs SRT, estimated SMD = 0.53

			Central, Fixed-Time (CFT) ‘Flash Word’ VHSS Treatment Group *n* = 9 with DD (2 L-type and 7 P-type only) Reversed Lateral Presentation (RevL) ‘Flash Word’ VHSS Treatment Group *n* = 13 (13 M-types) Right Hemisphere Lateral Presentation (RH) ‘Flash Word’ VHSS Comparison Group *n* = 13 with DD (3 L-types, 3 P-types, and 7 M-types) Standard Reading Treatment (SRT)			• CFT Vs SRT, estimated SMD = 0.73 • RH Vs SRT, estimated SMD = 0.67 Global Reading Rate (a composite of text, word and pseudoword reading rate tasks) For the P-type and L-type dyslexics, groups did not differ significantly in improvement following treatment, *ps* >.10 • SL Vs SRT, estimated SMD = -0.24 • RL Vs SRT, estimated SMD = -0.34 • C Vs SRT, estimated SMD = -0.58 • CFT Vs SRT, estimated SMD = 0.61 • RevL Vs SRT, estimated SMD = 0.02 For the M-type dyslexics, groups did not differ significantly in improvement following treatment, *ps* >.10 • SL Vs SRT, estimated SMD = -0.72 • RL Vs SRT, estimated SMD = -0.52 • C Vs SRT, estimated SMD = -0.44 • CFT Vs SRT, estimated SMD = -0.18 • RH Vs SRT, estimated SMD = -0.52
17	Luniewska et al., 2018	Age, IQ, Reading	Treatment Group *n* = 27 with DD AVG Comparison Group *n* = 27 with DD Phonological Video Game Control Group *n* = 16 with DD No Treatment	50 minutes sessions, completed across 22-36 days (16 sessions). Total = 13.3 hours	AVG and PNAVG groups: 0-7 days (M = 1.5) before treatment and 1 - 18 days (M = 4.8) following treatment Control group: 16-60 days apart (M = 38.3)	Outcomes compared between AVG and PNAVG groups: Word Reading Rate – Both the AVG and PNAVG groups improved following training, *p* = .001, SMD = 0.27 Word Reading Fluency – Both the AVG and PNAVG groups improved following training, *p* = .001, SMD = 0.18 Outcomes compared between AVG, PNAVG, and Control groups: Sentence Reading Comprehension – All groups improved significantly over time, *p* = .049, • AVG Vs PNAVG, SMD = 0.08 • AVG Vs Control, SMD = -0.03

						Groups were re-assessed one month later. Again, all groups improved significantly with time, $p < .001$
18	Meng et al., 2014	Age, IQ, Reading, Texture Discrimination were matched within the DD and TD groups respectively	Treatment Group $n = 9$ with DD Texture Discrimination Training Treatment Group $n = 9$ TD Texture Discrimination Training Control Group $n = 9$ with DD No treatment Control Group $n = 9$ TD No treatment	Treatment groups: 50 minute sessions, completed within 4 weeks (10 sessions). Total = 8.3 hours	N/A	Text Reading Fluency - Only the dyslexic treatment group improved significantly following the treatment period, $p < .05$ The dyslexic treatment group maintained improvement at a 2 month follow up assessment, $p > .1$.

Note. VHSS = Visual Hemispheric Specific Stimulation; AVG = Action Video Game; NAVG = Non-Action Video Game (Control Treatment); DDT = Direction Discrimination Training; TD = Typically Developing; DD = Developmental Dyslexia; Standard Reading Treatment refers to remediation programs commonly used by clinicians for the treatment of dyslexia that target reading sub-skills, such as phonological awareness, and teach guided reading and compensatory strategies; The Phonological Video Game training phonological skills and did not meet action video game criteria; SMD = Standard Mean Difference of change (also referred to as Cohen's d). Where an experimental treatment is compared to a control or comparison treatment, a positive SMD is in favour of the visuo-attention intervention, in studies with more than 2 groups, the SMD is in favour of the first intervention listed. Small = 0.2, medium = 0.5 and large = 0.8 effect sizes respectively.

2.4.5 Description of RAPs

The visually-based RAP studies used a variety of programs. These studies did not include explicit phonological training but do require children to read words and sentences (sometimes with feedback) and so cannot be said to be only reliant on visuo-attentional mechanisms. Further, the studies included only consist of those that investigated RAP interventions from a visuo-attentional perspective (thus meeting inclusion criteria). The program used by Das-Smaal, Klapwijk, and van der Leij (1996) required participants to view a briefly presented multi-letter unit then identify whether it was present in an ensuing word. Presentation time was decreased with correct responses (program adapted from Frederiksen, Warren, & Rosebery, 1985). Franceschini, Bertoni, Gianesini, Gori, and Facoetti (2017a) developed ‘The Library Tower’, an open access, sentence level program in the Italian language that required participants to read the sentence silently then answer a corresponding multiple-choice question, with presentation duration decreased with correct responses (for further information about the program 'The Library Tower', see Supplementary Information from Franceschini et al., 2017a). A commercially available program ‘Tachistoscopio’ was used by Judica, De Luca, Spinelli, and Zoccolotti (2002) and required participants to read single words then type the presented word, with presentation duration and word difficulty and length adjusted (program developed by Morchio, Ott, Pesenti, & Tavella, 1989). Visual Hemispheric Specific Stimulation (VHSS) was investigated by five of the included studies, (Facoetti et al., 2003; Lorusso et al., 2011; Lorusso et al., 2004; Lorusso et al., 2006; Lorusso, Facoetti, Toraldo, & Molteni, 2005), with most using a program called ‘Flash Word’ (developed by Masutto & Fabbro, 1995). Traditional VHSS presents words in the peripheral visual field and requires participants to read the word aloud, with presentation time, word length and complexity adjusted. Some VHSS variations used in the included studies manipulated whether words were presented centrally or peripherally, and whether presentation time was reduced or fixed. In addition to more recent evidence that VHSS induces visuo-attentional orienting via peripheral processing, VHSS is conventionally based on Bakkers theory of an imbalance in the hemispheric contributions to reading (Bakker, Moerland, & Goekoop-Hoefkens, 1990).

2.4.6 Description of VPT

Visual perceptual training studies comprised two treatment programs. Four studies, conducted by the program designer (Lawton, 2004), investigated direction discrimination training (DDT) using the commercially available program ‘PATH to reading’ and its precursor, ‘Moving to Read’. DDT uses a figure/ground motion discrimination paradigm and required the participant to view moving stripes (sinusoidal gratings) embedded at the centre of a striped background and discriminate the direction of movement. Contrast thresholds and spatial frequencies of the centre and background sinusoidal gratings were manipulated in all studies to increase complexity, and one study also manipulated the sinusoidal grating movement speed (See Figure 1 from Lawton & Shelley-Tremblay, 2017). DDT was designed to address visual timing deficits found in those with DD by maximally targeting the dorsal ‘where’ pathway and its M pathway projections. The high motion and low contrast components at low spatial frequency maximally activated M cells, while higher spatial frequency and higher levels of contrast were used in the program to increase parvocellular (P) type activity and task complexity. One study used texture discrimination training (TDT). TDT comprised a texture display made of high contrast horizontal line segments with either a randomly rotated letter ‘‘T’’ or ‘‘L’’ as the central fixation point (See Figure 1 from Meng, Lin, Wang, Jiang, & Song, 2014).

A briefly presented target array, in either the upper left or right visual field, was produced by rotating three horizontally or vertically adjacent bars in the texture stimuli to form either a horizontal or vertical form. The participant was required to identify both the fixation letter and direction of the target array. A 2-down 1-up staircase procedure was used to adjust the stimulus-to-mask onset asynchrony and determine participants' task threshold. TDT aimed to improve visual perceptual performance by training temporal processing speed, as well as visual span and spatial attention via high peripheral processing demands.

2.4.7 Description of AVGs

All investigations of AVGs used the same mini-games from the commercially available program 'Raymans Raving Rabbids' (see Ubisoft, 2006). Selected mini-games met the following AVG criteria, 1) speed; 2) high levels of cognitive, perceptual and motor load; 3) divided attention; and 4) high levels of peripheral processing (Green & Bavelier, 2012). Examples of the mini-games include first-person shooter style games where Rayman must shoot rabbid bunnies with a plunger gun in order to avoid being touched by the bunnies that appear unpredictably from any direction, go-no-go style games in which Rayman must sneak up a rabbid bunny while attending to fast visual cues, and labyrinth games where Rayman must navigate as quickly as possible without touching the sides of the maze (for a full list and description of mini-games used, see Supplementary Information from Franceschini et al., 2013). Four of the studies compared the AVG to a non-AVG (active control treatment using video games that did not meet AVG criteria) using 'Raymans Raving Rabbids' mini-games that did not satisfy AVG criteria, while the fifth study compared the AVG to an experimental phonological video game that trained phonological processing and did not meet criteria as an AVG, and a no treatment group.

2.5 Discussion

Out of 2288 records, 18 studies met the inclusion and risk of bias criteria for this review. The studies, while written in English, investigated reading outcomes across five languages, and included a heterogeneity of intervention durations, intervention intensity, comparison treatment groups and control groups, and reading outcomes. Quality of the included studies was generally fair, with non-randomised studies all assigned an overall moderate risk of bias (i.e., sound for a non-randomised study, but not comparable to a well-performed randomized trial) and randomised studies all assigned an overall low risk of bias. Only three studies evaluated the efficacy of visuo-attentional interventions of the reading outcomes of typically developing children, three studies included short-term follow-up assessments, and only one study investigated whether increasing intervention resulted in greater reading gains. Overall, the studies fell into three categories, VPT (n = 5), RAPs (n = 8), and AVGs (n = 5), and so have been summarised within each of the three groups.

2.5.1 Visual Perceptual Training (VPT)

Five of the included studies investigated the effectiveness of visual perceptual interventions for reading outcomes in a total of 199 children, of which 146 were dyslexic and 53 were typically developing (Lawton, 2004, 2008, 2016; Lawton & Shelley-Tremblay, 2017; Meng et al., 2014). These intervention stimuli each target low-level visuo-attention mechanisms and do not include any phonological, orthographic or reading involvement. Four of the studies, all by the same author, investigated DDT (Lawton, 2004, 2008, 2016; Lawton & Shelley-Tremblay, 2017), while the fifth study investigated the efficacy of TDT (Meng et al., 2014). Of the included visual perceptual training studies, two included established comparison treatments (Raz-Kids Guided Reading, FastForWord), two included active control treatments, two compared the intervention to a ‘no treatment’ group, and one study compared the target intervention between typically developing and DD children.

2.5.1.1 VPT results.

All five studies assessed **reading fluency** outcomes, with all reporting significant improvements in fluency as compared to established comparison treatments, and control groups. Effect sizes were only available for three of the studies and demonstrated large effect sizes in favour of DDT (Lawton, 2004, 2016; Lawton & Shelley-Tremblay, 2017). Typical and DD participants were shown to benefit similarly from DDT (Lawton, 2008; Lawton & Shelley-Tremblay, 2017); however, Meng et al. (2014) found that only dyslexic, not typically developing, participants improved following TDT. Further, Meng et al. (2014) found that the dyslexic group had maintained their gains in reading fluency at a two-month follow-up, while Lawton (2008) demonstrated that increasing intervention duration and intensity improved reading fluency outcomes significantly more.

Three of the DDT studies assessed **reading comprehension** outcomes, demonstrating that DDT improved comprehension in both TD and DD children significantly more than a guided reading comparison treatment ('Raz-Kids'; Lawton & Shelley-Tremblay, 2017), and improved comprehension in those with DD significantly more than control groups but not ‘FastForWord’ an auditory timing comparison treatment which improved comprehension more (Lawton, 2004, 2016).

No visual perceptual training study measured **reading rate** outcomes and only one of the included studies assessed **reading accuracy** (word level), demonstrating that DDT improved accuracy significantly more than control groups, with medium to large effect sizes found respectively (Lawton, 2004). One study assessed **reading grade level** outcomes following intervention and found the DDT group improved significantly more than control groups (Lawton, 2004). Large effect sizes in favour of DDT were found.

Together, results indicate that visual perceptual training is efficacious in improving reading comprehension and fluency in children with DD and may also be beneficial to typically developing children. Further studies assessing reading rate and accuracy would help elucidate the benefit of visual perceptual training programs on other reading outcomes. Although only tentative conclusions can be drawn regarding the impact of orthography on intervention efficacy due to the small number of studies, results suggest that children from both a deep alphabetic (English) and deep logographic orthography (Chinese) show similar benefits to reading fluency.

2.5.2 Reading Acceleration Programs (RAPs)

Eight of the included studies investigated the effect of interventions of computerized adaptive, rapid presentation of letter units, words or sentences, in a total of 278 dyslexic children (Das-Smaal et al., 1996; Facoetti et al., 2003; Franceschini et al., 2017a; Judica et al., 2002; Lorusso et al., 2011; Lorusso et al., 2004; Lorusso et al., 2006; Lorusso et al., 2005). What is of particular interest is that the list of included studies does not constitute all studies of RAPs but comprises the studies that have investigated these interventions from a visuo-attentional perspective and therefore have met the reviews' search terms and inclusion criteria. RAPs are argued to load working memory, rapid visual processes, attentional factors, and executive functions (Horowitz-Kraus et al., 2014), but do not include explicit phonological or orthographic training. While this group of interventions cannot be considered purely visuo-attentionally-based like the other groups of interventions included in this review, all of the included RAP studies discuss how the resulting reading improvements are mediated by improvements to visuo-attentional processing, more specifically, automatization of visual perceptual and attentional processing (Das-Smaal et al., 1996), global visual processing (Franceschini et al., 2017a; Judica et al., 2002), and rapid endogenous visuo-spatial orienting and inhibitory-controlled attentional focus (Facoetti et al., 2003; Lorusso et al., 2011; Lorusso et al., 2004; Lorusso et al., 2006; Lorusso et al., 2005). Three studies compared RAPs to a standard reading treatment (remediation programs commonly used by clinicians for the treatment of dyslexia that target reading sub-skills, such as phonological awareness, and teach guided reading and compensatory strategies), two compared various manipulations of RAPs to elucidate the processes which underpin treatment, two compared RAPs to a 'no treatment' control group, and one compared RAP to an active control treatment.

Variability in methodology between the RAP studies (i.e., whether the intervention was letter unit/word/sentence-based, comparison groups included, treatment duration) made synthesising the results particularly challenging, so results will be discussed based on outcomes.

2.5.2.1 RAPs results.

All RAP studies assessed either word or text **reading rate** outcomes, and one study assessed both word-level and text-level reading rate. Results show that RAPs significantly improved reading rate in seven of the nine reading rate outcomes measured, more than or equal to comparison treatments, or more than control groups. RAPs improved reading rate more than a standard reading treatment in one study (Facoetti et al., 2003) and comparably to standard reading treatments in two other studies (Lorusso et al., 2011; Lorusso et al., 2006). Various manipulations of VHSS did not significantly impact on treatment efficacy with all manipulations resulting in improved reading rate (Lorusso et al., 2011; Lorusso et al., 2004; Lorusso et al., 2005)

In contrast, results comparing RAPs to control groups were more variable. Franceschini et al. (2017a) found RAPs improved text reading rate significantly compared to no treatment, Judica et al. (2002) found that RAP only improved word reading rate, not text reading rate, as compared to no treatment, while Das-Smaal et al. (1996) found that RAP did not improve word reading rate outcomes. The five studies for which reading rate outcome effect sizes were available reported small to moderate effect sizes in favour of RAPs in comparison to control groups. Effect sizes were available for two of the three studies comparing RAPs to a comparison treatment option (Standard Reading Treatment; Lorusso et al., 2011; Lorusso et al., 2006). In both studies, each intervention had significantly improved reading rate outcomes comparably, and effect sizes ranged from negligible to moderate, with some (non-significantly) in favour of RAPs and others in favour of the comparison treatment.

All RAP studies assessed **reading accuracy** outcomes. Results show that RAPs significantly improved reading accuracy in seven of the nine accuracy outcomes measured, more than or equal to comparison treatments, or more than control groups. RAPs improved reading accuracy more than a Standard Reading Treatment in two studies (Facoetti et al., 2003; Lorusso et al., 2006), and improved comparably to a Standard Reading Treatment in another study (Lorusso et al., 2011). All types of VHSS improved reading accuracy (Lorusso et al., 2004; Lorusso et al., 2005), although type of VHSS affected the treatment efficacy (Lorusso et al., 2011). As compared to control groups, Judica et al. (2002) found RAP improved reading accuracy at both the word and text level as compared to no treatment, while the other two studies found that RAPs did not improve accuracy more than control (Das-Smaal et al., 1996) or did not improve significantly following treatment (Franceschini et al., 2017a). Studies for which effect sizes for reading accuracy outcomes were available reported moderate to large effect sizes in favour of RAPs in comparison to control groups, and mostly moderate to large effect sizes in favour of RAPs as related to established comparison treatments, although two manipulations of VHSS were (non-significantly) not as efficacious as the Standard Reading Treatment, with small effects sizes found.

Only the study by Das-Smaal et al. (1996) assessed **reading fluency** as an outcome, demonstrating a significant improvement only following RAP as compared to a control group. One study assessed **reading comprehension** outcomes, finding no improvement following treatment (Judica et al., 2002).

Together, the results are generally favourable for RAPs in improving the reading accuracy and rate of children with DD, although much more evidence comparing RAPs to both established comparison treatments as well as control interventions are necessary. Nevertheless, results from Franceschini et al. (2017a) provides initial evidence that performance following training is maintained two-months following treatment. More studies that assess reading fluency and comprehension outcomes are also warranted.

No conclusions regarding the impact of types and level of orthography on RAP efficacy for reading can be surmised as all eight studies were conducted in shallow orthographies (Italian and Dutch), highlighting a need for future studies to investigate RAPs in deep orthographies. Nonetheless, all eight studies concluded that RAPs are beneficial in improving aspects of reading. Authors concluded that RAPs work by improving rapid visual processing, leaving neural resources available for more global extraction of semantic visual information (Das-Smaal et al., 1996; Franceschini et al., 2017a; Judica et al., 2002; Lorusso et al., 2011; Lorusso et al., 2006; Lorusso et al., 2005), spatial attention (Facoetti et al., 2003; Lorusso et al., 2006; Lorusso et al., 2005), automatization (Das-Smaal et al., 1996; Lorusso et al., 2011; Lorusso et al., 2004; Lorusso et al., 2006), but also via non visuo-attentional mechanisms, including improvements to visual and auditory working memory and memory retrieval processes (Lorusso et al., 2004), appropriate use of reading strategies (Lorusso et al., 2011; Lorusso et al., 2004; Lorusso et al., 2006), and specific effects of hemispheric stimulation (Lorusso et al., 2011; Lorusso et al., 2006). Thus, while it is clear that visuo-attentional processes clearly underpin the RAPs, the relative importance of visuo-attention remains unclear.

2.5.3 Action Video Games (AVGs)

Five studies investigated the efficacy of AVGs on the reading skills of a total of 143 dyslexic children (Franceschini et al., 2017a; Franceschini et al., 2013; Franceschini et al., 2017b; Gori et al., 2016; Luniewska et al., 2018). AVGs load both temporal and spatial visuo-attention (Green & Bavelier, 2012), and have been shown to result in generalised visuo-attentional improvements beyond the trained task (Green & Bavelier, 2003; Li, Polat, Makous, & Bavelier, 2009; West, Stevens, Pun, & Pratt, 2008), enlarging capacity and spatial distribution of visuo-attention, and improving rapid discrimination of sequential visual stimuli and visual motion sensitivity (Green & Bavelier, 2003; Pavan, Boyce, & Ghin, 2016). The AVG used across the studies also do not require or explicitly train any phonological, orthographic or reading processes in order to play the games, and so any improvements to reading outcomes can only be attributed to attentional enhancement. Additionally, children typically enjoy playing video games, and so AVGs could provide a treatment option that not only does not feel like an intervention but is also highly engaging and intrinsically motivating for children.

2.5.3.1 AVG results.

Results show that as compared to a control group who played non-AVGs (video games that do not meet criteria as ‘action-based’), only AVGs significantly improved **reading rate,** with moderate-to-large effect sizes found (Franceschini et al., 2017a; Franceschini et al., 2013; Franceschini et al., 2017b). The AVG also performed comparably to a phonological video game comparison treatment that trained phonological skills and did not meet AVG criteria, with both treatments improving reading rate significantly (Luniewska et al., 2018). Inspection of the SMD between the AVG and phonological video game interventions showed that the small effect size, although non-significant, was in favour of the AVG.

Both studies that assessed **reading accuracy** outcomes found that the AVG did not improve accuracy more than the non-AVG control group, although the one study for which a SMD was available found a large effect size between the groups (Franceschini et al., 2017a; Franceschini et al., 2017b).

Three AVG studies measured **reading fluency** outcomes. Reading fluency only improved significantly for the AVG treatment and not the non-AVG control group, with large effect sizes found in the two studies (Franceschini et al., 2013; Gori et al., 2016). In contrast, Luniewska et al. (2018) found that reading fluency was improved by both AVG and the phonological video game comparison treatment options, although the small effect size was in favour (non-significantly) of AVG treatment.

Only Luniewska et al. (2018) assessed **reading comprehension** outcomes following AVG, compared with a phonological video game, and a no treatment control group. Results show that all groups improved over the treatment period, and also at a one-month follow-up assessment, suggesting that neither AVG nor phonological video game promoted reading comprehension any more than age development alone. Effect sizes between the three groups were negligible.

Taken together these results suggest that AVGs are efficacious in improving reading rate and fluency, but may not benefit reading accuracy or comprehension, although more studies are needed to establish interpretations. Interestingly, while most studies concluded that AVGs are beneficial in improving aspects of reading, Luniewska et al. (2018) concluded that AVG and phonological video games do not improve reading more than ‘no treatment’, because the groups performed comparably across web-based outcome measures (reading comprehension, real word recognition, pseudoword decoding). Yet, there are other plausible explanations. Standardised reading fluency and rates measures were only assessed in the two treatment groups, while an experimental web-based reading comprehension measure (as part of a larger battery) was used to assess and compare all three groups and was overseen by each child’s parent (Luniewska et al., 2018). Thus, different reading skills were assessed and compared between the groups, and the reliability or testing conditions of the experimental web-based task is not clear. Furthermore, reading rate and fluency outcomes improved in dyslexic children across AVG studies, regardless of shallow (Italian) or deep (English & Polish) orthography.

2.5.4 General Limitations and Future Directions

There were several frequent and concerning limitations to this review. Sample size is a common limitation across the three types of visuo-attentional interventions and thus impacts on the strength of the conclusions that can be drawn by this review. Most studies did not provide sufficient information in their original paper to permit adequate appraisal of some risk of bias domains. Hence all included study researchers were contacted to provide further information as well as information pertaining to study methodology and outcomes. Most non-randomised studies were assigned a moderate overall risk of bias (Sterne et al., 2016), often due to cautious interpretation of the ‘reported result’ domain, following the lack of a pre-specified protocol. Randomised studies were largely assigned low risk of bias to most outcomes and low risk of bias overall, although reporting of randomisation and allocation concealment methods was almost always insufficient. Future non-randomised studies need to improve the reporting of whether confounding domains were controlled for before the study, and how measurement of outcomes were protected from bias, while future randomised studies should improve reporting of random sequence generation and allocation concealment methods. Future studies should also report sufficient information to facilitate quality assessment and should consider pre-registering their study to reduce potential bias in the reporting of results and bias towards only publishing significant results. Very few studies provided SMD or other measures of effect size in their original article. Many of the included studies were conducted by the same author or groups of authors, inflating the potential for non-independence. As only published studies were included in the current review, the presence of publication bias is not clear. Future studies should also consider using standardised reading measures over experimental measures to improve comparisons across studies.

A meta-analysis was not considered appropriate for several reasons. Six of the included papers did not provide sufficient information to be included in a meta-analysis, and others did not provide sufficient information for all primary reading outcomes included. Therefore, the number of papers would be reduced significantly in terms of quantitative information for any meta-analysis, and thus the breadth of research that has been conducted in this area would not be captured. The heterogeneity of the interventions assessed (including within our sub-groups), treatment durations within same/similar interventions (e.g., 1-30 hours within studies assessing direction discrimination training), and reading outcomes measured are also substantial, representing serious limitations that would negatively affect the impact of the meta-analytical results. Once further studies are available, including one by the review authors, an update to this qualitative review and inclusion of a quantitative meta-analysis will be conducted.

Nonetheless, there were also a number of strengths to the studies included. Most of the studies used robust dyslexia criteria, often citing the DSM or ICD and using conservative diagnostic cut-off scores such as > 1.5 or > 2 standard deviations. Studies also generally matched groups on important covariates known to impact on reading development, such as age and intelligence, which would otherwise be likely to result in confounding of intervention findings. Across the three intervention groups, intervention durations were brief, 1–30 hours for visual perceptual training, 6.3 – 35 hours for RAPs, and only 12 – 13.3 hours for AVGs. This would suggest that visuo-attentional interventions may prove to be efficacious much more quickly than other current, more traditional and time-intensive intervention options (Gabrieli, 2009). Further investigation into whether longer durations of visuo-attentional intervention would increase efficacy would be beneficial.

2.6. Conclusions

The results of this review show that visuo-attentional interventions for dyslexia, though brief, are able to produce significant reading gains, without the need for explicit phonological or orthographic instruction, and for VPT and AVGs, also without any reading component. The patterns of evidence show that VPT programs provide most benefit for reading fluency and comprehension, visually-based RAPs appear to improve reading accuracy and rate, while AVGS result in gains to reading rate and fluency. Moreover, improvements following visuo-attentional interventions are generally equal to or greater than other intervention options. The current literature, while limited, also suggests that visuo-attentional interventions can produce reading improvements that are maintained for at least two months following treatment and may also improve the reading skills of typically developing children. Emergent evidence also indicates that visuo-attentional interventions benefit reading outcomes in both shallow and deep orthographies.

Additional high quality studies are needed to compare visuo-attentional treatments to both control and established comparison treatments and, importantly, to permit meta-analysis and further establish treatment efficacy in dyslexia. Investigations should also aim to assess intervention benefit on a wide range of reading outcomes over longer time using larger samples to better establish the duration and breadth of benefit to reading skills. While AVGs and VPT specifically target visuo-attentional mechanisms, further investigation into the various higher-level cognitive contributions in visually-based RAPs is also needed to better elucidate the role of visuo-attentional mechanisms in most cognitive activities. In sum, visuo-attentional interventions can be considered effective options for treating dyslexia in childhood. From a clinical perspective, while phonologically-based interventions are efficacious for young children as they remediate single word accuracy and letter-sound knowledge (i.e., skills important for learning to read), computerized visuo-attention interventions may be more efficacious to children who need to develop automaticity (i.e., rate and fluency) as required to become a proficient reader. The evidence obtained from the studies included in this review indicates that visuo-attentional deficits are contributing factors of dyslexia.

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2.9 Conflicts of Interest

None.

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CHAPTER 3

Methodological Choices

3.1 Chapter Overview

Specific details regarding the method used in each study are provided in the relevant chapters of this thesis. This chapter provides additional information pertaining to the key methodological choices. It specifically addresses the choice of population, diagnostic criteria, and the choice of experimental measures.

3.2 Choice of Population

The reading ability of children in the first years of schooling has been the focus of most reading research to date (Ricketts, Lervåg, Dawson, Taylor, & Hulme, 2020). Not only is reading still developing in this age group, making it possible to investigate the skills that contribute to reading development, but intervention is likely to be of most benefit at this age (Foorman, Francis, Shaywitz, Shaywitz, & Fletcher, 1997; Snowling, 2013). Therefore, the current thesis investigated a population of 237 children ranging from 5;09 to 13;01 years of age, in Grades Prep to 6 (i.e., the first seven years of formal schooling). This included 97 children who met diagnostic criteria (see below) for developmental dyslexia (*M*age = 9.45, *SD* = 1.65; 57.7% male), and 140 neurotypical children (*M*age = 8.29, *SD* = 1.73; 48.6% male). The participants included in the research reported in Chapter 5 consisted of an independent sub-sample of the aforementioned population, while the research reported in Chapters 4 and 6 included partially overlapping sub-samples of the aforementioned population: some dyslexic children who participated in the experimental study presented in Chapter 4 also participated in the intervention study presented in Chapter 6.

3.3 Diagnostic Criteria

A comprehensive approach to confirming diagnoses of dyslexia was undertaken throughout the current thesis, in accordance with the 5th edition of the

Diagnostic and Statistical Manual of Mental Disorders (DSM-5; American Psychiatric Association., 2013). DSM-5 advises that as academic skills and intelligence fall on a continuum, a cut-off point for the diagnosis of dyslexia is to some extent arbitrary (American Psychiatric Association., 2013; Cotton & Crewther, 2009). Instead they suggest the use of clinical judgement, evidence of low achievement (e.g., 1-2.5 *SD* below age-standardized normative data in one or more areas of reading), and other lines of converging evidence (e.g., a history of reading difficulties). Thus, this thesis not only employed a cut-off point of at least 1 *SD* below age-standardized normative data in one or more areas of reading, but also required either a previous diagnosis of dyslexia or reported history of reading difficulties. This mitigated the risk of false positives since inclusion as a dyslexic participant was not simply based on the a single timepoint of testing data.

3.4 Exclusion Criteria

The aim of this thesis was to examine differences in magnocellular (M) pathway processing and the rate of visual attention engagement and shifting in children with dyslexia as compared to neurotypical children. Participants were excluded if they did not have normal intelligence (Standard score ≥ 85 for age on the Raven's Coloured Progressive Matrices test), normal or corrected-to-normal vision and hearing, or English as their primary language, due to the potential impact of each of these factors on reading (Carroll & Breadmore, 2018; Carver, 1990; Douglas, Grimley, Hill, Long, & Tobin, 2002; Droop & Verhoeven, 2003; Thurston, 2014). Children with known medical and neurodevelopmental disorders other than dyslexia (e.g., ASD, ADHD) were also excluded. This information was obtained via parent and teacher report. It is important to note that all participants were included in the study testing if their parent signed the consent forms to ensure no child felt excluded, with results excluded from data analysis if the participant met any of the exclusion criteria.

3.5 Choice of Screening Measures

3.5.1 Vision

As ability to see well and with ocular comfort is a necessity in learning to read, both near and far visual acuity was ensured. A Snellen eye chart was used to assess distance vision at 6 metres, while near vision was assessed using a test card comprising letters of size 8 font. The Ishihara Colour Test, consisting of twenty-four psychochromatic plates, was used to provide a quick assessment of color vision deficiency. Participants who displayed any difficulties on the vision screening measures were then formally screened by an optometrist. Summary letters were provided to parents/guardians for any child requiring follow-up care or assessment.

3.5.2 Hearing

Adequate hearing was indicated by parent report of no history of hearing difficulties and by the ability of participants to satisfactorily comprehend and follow verbal instructions.

3.5.3 Intelligence

Nonverbal intelligence was assessed using the Ravens Coloured Progressive Matrices for participants aged 5-11 years (Raven, Court, & Raven, 1998) or the Ravens Standard Progressive Matrices for participants aged ≥12 years (*Standard Progressive Matrices: Australian Manual*, 1958). Each test contains series of matrices of increasing complexity. Age-based standard scores were calculated using normative data. The Ravens matrices have been standardized in a number of countries including Australia, and considered appropriate for children with reading disorders (Cotton et al., 2005).

3.6 Experimental Tasks

The aim of this thesis was to explore M pathway processing thresholds and the rate of visual attention engagement and shifting, in dyslexic and neurotypical children. Therefore, several experimental measures that assess the rate of the M pathway and visual attention were chosen, in addition to well-established measures of reading and reading-related skills. These tasks are described in detail below.

3.6.1 Reading

While a great deal of reading research (e.g., see outcome measures of studies included in McArthur et al., 2018; Peters, De Losa, Bavin, & Crewther, 2019)has employed tasks of single word, pseudoword, and regular/irregular word reading lists in order to investigate reading processes, research conducted for this thesis instead utilized tasks related to text reading. This is because the ability to read connected and meaningful text is the ultimate measure of reading ability and relies on all contributing attentional and cognitive skills to work rapidly and accurately to facilitate reading, permitting a more thorough investigation into the relationship between rate of visual processing and reading. Both the Neale Analysis of Reading Ability – Third Edition (NARA-3) and the York Assessment of Reading for Comprehension, Primary Passage Reading – Australian Edition (YARC) were included in the research undertaken. Both tasks similarly assess oral text reading accuracy, rate and comprehension using a series of passages that increase in difficulty and are appropriate for use with children in the first seven years of formal schooling. The choice to use different text reading tasks was based on the specific requirements of each study. The YARC was included in the studies presented in Chapters 4 and 6 as it typically has a shorter administration time compared with the NARA-3 when assessing children from upper primary school years, as was the sample of participants included in those studies. While the NARA-3 requires the reader to continue to read passages of increasing difficulty until a passages' threshold of reading errors is reached, which often requires older children to read several passages, the YARC only requires that two passages be read successfully (i.e., without reaching the passages error threshold). Not only did this reduce administration time, it also reduced the amount of reading dyslexic participants were required to complete so as not to be unduly onerous or anxiety producing. In contrast, the NARA-3 was more practical for use in the younger sample of children (Grades Prep to 2) who participated in the study reported in Chapter 5. It was anticipated that some children included in the study (i.e., particularly those only in their first year of schooling) may only be able to pass the first passage. This is adequate for scoring on the NARA-3, while the YARC requires two passages to be read and is not able to generate a measure of reading rate based on the first (i.e., beginner) passage.

3.6.2 Reading-Related Tasks

Phonological awareness (Melby-Lervåg, Lyster, & Hulme, 2012; Suárez, 1996) and rapid automatic naming (RAN; Denckla & Rudel, 1974) are both well-established predictors of reading (Landerl et al., 2019). Phonological awareness was assessed using the elision subtest, a sound deletion task, from the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999; Wagner, Torgesen, Rashotte, & Pearson, 2013). This task was chosen over other phonological awareness subtests from the CTOPP as it demonstrates the highest level of internal consistency with the broader phonological awareness composite across the age range of participants used in the studies of this thesis (Wagner et al., 2013). Rapid naming was assessed using the serial number RAN task from the CTOPP (Chapters 4 and 6) as well as a customized serial letter RAN task (Chapter 5). The choice to include a custom 60 second RAN task in the study reported in Chapter 5 was to ensure that a sufficient and equal duration of eye tracking data was recorded to better facilitate comparisons and analysis.

3.6.3 Temporal Processing Thresholds

Achromatic Flicker Fusion Threshold (FFT) tasks were chosen as they are the simplest test of M-stream temporal processing thresholds for neural recovery to repeated stimulation (Hecht & Shlaer, 1936). Specifically, the low (5%) and high contrast (75%) FFT tasks used in the experimental studies included in this thesis were adopted from Brown, Corner, Crewther, and Crewther (2018), a study which established that performance on the tasks were specifically related to the M pathway functioning. In this thesis, task performance was used to determine whether dyslexic and neurotypical children display differences in temporal processing thresholds, and to elucidate how temporal processing may relate to reading skills. Further task details are provided in Chapters 4 and 6.

3.6.4 Eye Movements

Eye movement were included in the research conducted within this thesis as they provide a task-based measure of temporal and spatial visual attentional shifting (Casteau & Smith, 2020). Patterns of eye movements are known to be impaired in those with dyslexia (Al Dahhan et al., 2014; Al Dahhan, Kirby, Brien, & Munoz, 2016; Rayner, 1998), and provide valuable information pertaining to rate of visual processing, with fixation duration reflecting the duration of attentional engagement (Eckstein, Guerra-Carrillo, Miller Singley, & Bunge, 2017; Kim, Petscher, & Vorstius, 2019), and fixation count representing the spatial distribution of attention (i.e., the amount of visual information processed in each fixation; Goldberg & Kotval, 1999; Holland & Komogortsev, 2011; Rayner, Ardoin, & Binder, 2013). In the experimental chapters of this thesis, eye movements were recorded during rapid naming, which is considered a surrogate measure of reading aloud without the confounds of additional factors known to impact upon eye movement patterns, such as word length, familiarity or difficulty (Kuperman & Van Dyke, 2011). A Gazepoint screen mounted infrared camera (Gazepoint) was used to binocularly track vertical and horizontal eye positions with an average gaze position accuracy of 0.5 degrees. Further task details are provided in Chapters 5 and 6.

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CHAPTER 4

Flicker Fusion Thresholds as a Clinical Identifier of a Magnocellular-Deficit Dyslexic Subgroup

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The published version and the supplementary information for this paper are provided in Appendix H and I, respectively.

4.1 Abstract

The magnocellular-dorsal system is well isolated by high temporal frequency. However, temporal processing thresholds have seldom been explored in developmental dyslexia nor its subtypes. Hence, performances on two, four-alternative forced-choice achromatic flicker fusion threshold tasks modulated at low (5%) and high (75%) temporal contrast were compared in dyslexic and neurotypical children individually matched for age and intelligence (8-12 years, n = 54 per group). As expected, the higher modulation resulted in higher flicker fusion thresholds in both groups. Compared to neurotypicals, the dyslexic group displayed significantly lower ability to detect flicker at high temporal frequencies, both at low and high temporal contrast. Yet, discriminant analysis did not adequately distinguish the dyslexics from neurotypicals, on the basis of flicker thresholds alone. Rather, two distinct dyslexic subgroups were identified by cluster analysis – one characterised by significantly lower temporal frequency thresholds than neurotypicals (referred to as 'Magnocellular-Deficit' dyslexics; 53.7%), while the other group ('Magnocellular-Typical' dyslexics; 46.3%) had comparable thresholds to neurotypicals. The two dyslexic subgroups were not differentially associated with phonological or naming speed subtypes and showed comparable mean reading rate impairments. However, correlations between low modulation flicker fusion threshold and reading rate for the two subgroups were significantly different (p = .0009). Flicker fusion threshold performances also showed strong classification accuracy (79.3%) in dissociating the Magnocellular-Deficit dyslexics and neurotypicals. We propose that temporal visual processing impairments characterize a previously unidentified subgroup of dyslexia and suggest that measurement of flicker fusion thresholds could be used clinically to assist early diagnosis and appropriate treatment recommendations for dyslexia.

4.2 Introduction

Developmental Dyslexia is a heterogenous neurodevelopmental disorder affecting ~10% of individuals, who are characterized by impaired reading accuracy, speed and comprehension, i.e. dysfluency (American Psychiatric Association., 2013). While dyslexia has most often been associated with impairments in phonological processing (Snowling, 2001; Vellutino, 1979), the three most common models of dyslexia propose several distinct subtypes (Boder, 1970; Castles & Coltheart, 1993; Wolf & Bowers, 1999). (1) A phonological deficit subtype also referred to as dysphonesia; (2) visually-based subtypes characterized by either an orthographic (i.e., dyseidesia or surface dyslexia; Boder, 1970; Castles & Coltheart, 1993) or rapid naming speed deficit (Wolf & Bowers, 1999); (3) combination subtypes with both phonological and orthographic deficits (referred to as dysphoneidesia or mixed dyslexia; Boder, 1970; Castles & Coltheart, 1993) or both phonological and rapid naming deficits (referred to as a 'double-deficit'; Wolf & Bowers, 1999); and (4) a 'no-deficit' subtype where those with dyslexia do not display phonological, orthographic or naming speed deficits despite significant reading difficulties.

Although less accepted, converging lines of evidence also implicate visual impairments in dyslexia across mechanisms specifically associated with the magnocellular (M) pathway of the retinocortical dorsal visual stream (Crewther, Crewther, Barnard, & Klistorner, 1996; Gori, Seitz, Ronconi, Franceschini, & Facoetti, 2016; Laycock, Crewther, & Crewther, 2012; Lovegrove, Bowling, Badcock, & Blackwood, 1980; Lovegrove et al., 1982; Rutkowski, Crewther, & Crewther, 2003; Stein, 2001, 2019; Stein & Walsh, 1997; Vidyasagar & Pammer, 2010), with some suggesting that M-based impairments may only be experienced by a subgroup of dyslexic individuals (Hogben, 1996). However, the Magnocellular

Theory of Dyslexia has remained somewhat contentious due to variability in findings and difficulty isolating the faster conducting M pathway that contributes to both the dorsal and ventral visual streams (Johannes, Kussmaul, Münte, & Mangun, 1996; Skottun, 2000; Skottun, 2013, 2015; Vanni, Uusitalo, Kiesila, & Hari, 1997; Victor, Conte, Burton, & Nass, 1993). As yet, there is no well-established psychophysical measure of both spatial and temporal aspects of magnocellular-dorsal stream function that could be employed clinically to aid diagnosis of dyslexia and help guide appropriate interventions.

Indeed, temporal threshold manipulations, as compared to other proxies for M function properties such as low spatial frequency or low contrast performance have seldom been used to explore dyslexia. This is despite primate single cell physiological studies showing that the M stream is best isolated by stimuli presented at fast temporal frequencies (Bullier, Hupé, James, & Girard, 1996; Merigan & Maunsell, 1990; Schiller, Logothetis, & Charles, 1990), and evidence from Klistorner, Crewther, and Crewther (1997) using multifocal Visually Evoked Potentials to show distinct temporally limiting stimulus recovery characteristics of the M and Parvocellular (P) pathway contributions to the primary visual cortex (V1) in humans (see also Brown, Corner, Crewther, & Crewther, 2018; Livingstone, Rosen, Drislane, & Galaburda, 1991). Where moving stimuli, such as in motion coherence tasks, have been used to study dyslexia, paradigms have usually been studied at frequencies well below the ~15 Hz needed to isolate M from P contributions in primates (Merigan & Maunsell, 1990) and humans (Greenaway, Davis, & Plaisted-Grant, 2013; Skottun & Skoyles, 2006; Stein & Walsh, 1997; Wisowaty, 1981). Moreover, the low contrast and spatial deficits often seen in dyslexic individuals have been reported to become more apparent at increasingly higher temporal frequencies (Felmingham & Jakobson, 1995;

Martin & Lovegrove, 1987), though only under certain conditions (Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001). Hence, we propose that it may be the temporal processing properties of the magnocellular-dorsal system that is of greatest importance to reading, and that psychophysical tasks of temporal processing thresholds may prove to be the most valid and opportunistic, non-invasive tests of magnocellular sensitivity currently available.

The simplest test of temporal processing threshold for neural recovery to repeated stimulation is the Flicker Fusion Threshold (FFT) task which assesses the absolute temporal processing threshold at which rapid modulation of flickering light is no longer detectable– i.e., the point of fusion (de Lange Dzn, 1954; Hecht & Shlaer, 1936). The high temporal and extremely low spatial properties of an achromatic FFT task means that the point of fusion is set by the speed of neural recovery of the faster M cells in the primary visual cortex (Merigan, Byrne, & Maunsell, 1991; Solomon, Martin, White, Ruttiger, & Lee, 2002). Indeed, Brown and colleagues (2018) demonstrated in neurotypical adults that temporal processing of achromatic low and high contrast FFTs correlate with M (but not P) nonlinear visual evoked potentials. The point of achromatic fusion is reported to occur between 35-64 Hz and is contingent on the luminance, size of lighting source and depth of modulation (de Lange Dzn, 1954; Hecht & Shlaer, 1936; Seitz, Nanez, Holloway, & Watanabe, 2006), and age (Kim & Mayer, 1994; Tyler, 1989). FFTs have also been shown to be related to auditory temporal resolution and word decoding ability in typical readers (Au & Lovegrove, 2001; Holloway, Náñez, & Seitz, 2013), but to our knowledge, only five studies have compared the FFT performance, also referred to a critical flicker fusion, of individuals with dyslexia and typical readers (Brown, Peters, Parsons, Crewther, & Crewther, 2020; Chase & Jenner, 1993; Edwards et al., 2004;

McLean, Stuart, Coltheart, & Castles, 2011; Talcott et al., 1998). Four of these studies found that on flicker fusion tasks using M-preferred stimuli, dyslexics displayed significantly lower temporal frequency thresholds (i.e., lower sensitivity) as compared to a typical reader group, but that FFTs for P-preferred tasks were not different where evaluated (see Supplementary Table S1 for a summary of each study).

Thus, the present study aimed to clarify the importance of rate of magnocellular processing for reading performance using FFTs, and to establish the utility of FFT tasks as a potential clinical measure of dyslexia, either in general or as a classifier of subtypes. Hence, we have compared the achromatic temporal processing thresholds of dyslexic children and neurotypical children (with normal reading skills), individually matched on age and nonverbal intelligence. The two achromatic FFT tasks modulated at high (75%) and low (5%) contrast were adopted from Brown and colleagues (2018) and used as measures of the temporal frequency threshold (i.e., Hz) of M processing efficiency. Classification of dyslexic subtypes based on the presence and or absence of phonological awareness and rapid naming speed deficits (referred to as the Double-Deficit Hypothesis), was employed to identify if impairments in temporal processing of the visual system may be related to these previously proposed subtypes.

Specifically, the study aimed to explore the following research questions:

(i) Can FFT performance using low and high contrast achromatic FFT tasks dissociate groups of dyslexic and neurotypical children? And are there subgroups of dyslexic children with and without temporal processing (i.e., FFT) deficits?

(ii) If subgroups are present, are they associated with previously described subtypes of dyslexia?

(iii) Can FFT be used to discriminate dyslexic children with temporal deficits from neurotypical children and hence be established as a clinically useful test of magnocellular-dorsal functioning?

4.3 Method

4.3.1 Participants and Procedure

A total of 58 dyslexic children and 70 neurotypical children with normal reading ability between the ages of 8-12 years, from Grades 3-6, participated in the study. Of those, 54 dyslexics and 54 neurotypicals were able to be one-to-one matched within $\pm$0.73 *SD* of nonverbal intelligence, and within $\pm$1 year of age, and these 108 children were included in the analyses (See Table 1 for descriptives and group comparisons).

Table 1. *Descriptives and Comparisons of Dyslexic and Neurotypical Children*

	Dyslexic Children (N = 54)			Neurotypical Children (N = 54)					
	M	*SD*	*Range*	*M*	*SD*	Range	*t* (106)	*p*	*d*
Age	10.14	1.20	8.00-12.92	9.86	1.13	8.00-12.17	-1.25	.219	0.24
Nonverbal intelligence	104.50	8.02	88-121	106.70	10.19	85-121	1.5	.215	-0.24
Reading Accuracy	77.08	7.85	69-99	100.74	10.25	80-120	13.38	<.001**	-2.59
Reading Rate	76.00	8.71	69-103	99.96	9.89	80-124	13.22	<.001**	-2.57
Reading Comprehension	91.53	15.28	69-131	104.72	11.79	81-131	5.01	<.001**	-0.97
Phonological Awareness	87.52	11.61	70-116	103.33	11.16	85-125	7.15	<.001**	-1.39
Rapid Naming	83.14	11.14	58-104	95.26	12.41	69-118	5.24	<.001**	-1.03

Note: All scores, except for age, are reported as standard scores; Cohen's $d \geq 0.2$, $d \geq 0.5$, and $d \geq 0.8$, represent small, medium, and large effect sizes, respectively.

Participants were recruited and assessed at Melbourne metropolitan primary schools and an extra-curricular summer education program for those with reading difficulties between 2017 and 2018. All participants had normal intelligence (Standard score ≥85 for age on the Raven's Coloured Progressive Matrices test), normal or corrected-to-normal vision and hearing, and English as their primary language. Children with known medical and neurodevelopmental disorders other than dyslexia (e.g., ASD, ADHD) were excluded. To be included in the dyslexic sample, participants required 1) a history of reading difficulties as reported by teachers or parents and/or a formal diagnosis of dyslexia, and 2) reading performance at least 1.25 *SD* (O'Brien, Wolf, & Levett, 2012) below age-standardized norms in one or more area of reading (text reading accuracy, rate and/or comprehension) on the York Assessment of Reading for Comprehension - Primary Reading (YARC; Snowling et al., 2012), as confirmed by a psychologist on the research team. Parents of participants provided written informed consent for their child to engage in the study and all children who participated provided verbal assent. Testing occurred in a quiet, light-controlled room either at the child's school or at the site of the educational program, with tasks administered in randomized order. The experiment was performed in accordance with relevant guidelines and regulations and with ethics approval granted by the La Trobe University Faculty Human Ethics Committee and the Victorian State Department of Education.

4.3.2 Materials

4.3.2.1 Neuropsychological tests.

Nonverbal intelligence was assessed using the Raven's Coloured Progressive Matrices (Raven, Court, & Raven, 1998). The YARC was used to assess text reading accuracy, rate and comprehension skills (Snowling et al., 2012). The elision subtest, a measure of phonological awareness, and the rapid symbolic naming composite, consisting of letter and number rapid naming tasks, from the Comprehensive Test of Phonological Processing, 2nd Edition (CTOPP-2; Wagner, Torgesen, Rashotte, & Pearson, 2013) were administered to investigate relationships between FFT and reading-related skills and to classify dyslexic participants into subtypes as based on the Double-Deficit Hypothesis(Wolf & Bowers, 1999). All psychometric measures are reported as standardized scores obtained from the norm referenced instruments.

4.3.2.2 Temporal processing thresholds.

Two achromatic FFT tasks, modulated at high (75%) and low (5%) contrast in separate experimental tasks, were used. Four LEDs (A-Bright Industrial Co., China, part AL-513W3c-003 white) conveyed light into separate 6 mm diameter optic fibre light guides which were presented flush in a free-standing wooden panel in a diamond-array subtending 1.0◦, center-to-center, at the eye. The task was designed with VPixx software and flicker modulation was controlled via a DATAPixx device (10 kHz sampling allowed for smooth temporally modulated sinusoidal waveforms with frequencies in excess of 100 Hz). A gaussian temporal envelope (Full width at half maximum = 480 ms) was used to smooth the onset and offset of the flicker to prevent the alerting of change sensitive mechanisms and each light was calibrated for luminance. Each task consisted of a four-alternative forced-choice deign with 32 trials and used a Parameter Estimation by Sequential Testing. (For further details about task design, see Brown et al., 2018).

Participants completed the task at a viewing distance of 60 cm in a dimly lit room. They were instructed that one LED light per trial (demarcated by a high-pitched beep) would flicker for 3 seconds and at the end of the trial (indicated by a low-pitched beep) they were required to indicate which light source they saw flicker or guess when they were unsure. Prior to task commencement, participants were provided a practice session to familiarize them. During the tasks, the start of each trial was manually controlled by the experimenter to ensure participants were attending, and the onset of a trial began with a high pitch beep and finished with a low pitch. The order of high and low contrast conditions was counterbalanced to control for practice effects.

4.4 Results

4.4.1 Data Analysis

An *a priori* power analysis indicated that with a total of 90 participants (e.g., 45 per group) there was 95% power to detect a moderate effect size at p =.05. Data screening of the complete dataset identified several outliers that were just outside the normal distribution. These outliers were treated using the Winsorization method, i.e., they were recoded to the largest value within the normal distribution to reduce the influence on parametric statistical analyses (Tabachnick & Fidell, 2013). Normality was confirmed via assessment of skewness and kurtosis values, Shapiro-Wilk values, and visual inspection of histograms, Normal Q-Q plots and box plots. Cook distances were used to identify influential outlying data points in the correlational analyses; these data points were then removed from the relevant correlations. Preliminary analyses revealed no further violations of assumptions for the conducted analyses. Bonferroni adjustments were applied to the alpha level where multiple comparisons were conducted.

4.4.2 Can Differences in Temporal Processing Dissociate Groups of Dyslexic and Neurotypical Children?

Results of the multivariate analysis of variance show dyslexic children to have significantly lower flicker fusion sensitivity (i.e., slower temporal processing) at both

75% and 5% contrast as compared to the neurotypical children, both in the main multivariate analysis and subsequent univariate analyses, with moderate effect sizes (See Table 2).

Table 2. *Comparison of Flicker Fusion Thresholds in Dyslexic and Neurotypical Children*

	Dyslexic Children (n = 54)	Neurotypical Children (n = 54)				
	M (SD)	*M (SD)*	*F*	*df*	*p*	*d*
Multivariate analysis	-	-	4.36	2, 105	.015*	0.50
75% FFT	48.18 (4.27)	50.41 (4.58)	6.93	1, 106	.010**	0.51
5% FFT	45.16 (4.52)	47.22 (3.62)	6.56	1, 106	.012*	0.50

Note. Bonferroni adjusted alpha level of *$p < .016$, **$p \leq .01$; Cohen's $d \geq 0.2$, $d \geq 0.5$, and $d \geq 0.8$, represent small, medium, and large effect sizes, respectively.

Discriminant function analysis was used to identify whether FFTs could dissociate dyslexic children from neurotypicals. Results demonstrated that FFT sensitivity significantly differentiated dyslexic and neurotypical children, $\lambda = .923$, $\chi^2(2) = 8.367$, $p = .015$, $R^2 = .077$, with both the high contrast ($r = .888$) and low contrast tasks ($r = .863$) loading highly onto the discriminant function. However, the classification accuracy of the model was low. In total, 56.6% of dyslexic and 61.1% of neurotypical children were accurately classified. Overall, the model showed only a 58.9% classification accuracy. Thus, further analysis was conducted to identify if there were subgroups in the dyslexic sample.

4.4.3 Are there Subgroups of Dyslexic Children with and without Temporal Processing Deficits?

Two-step cluster analysis based on the high and low contrast FFT performance of the dyslexic sample revealed a two-cluster solution. The analysis used a log-likelihood distance measure approach with Schwarz's Bayesian Criterion (Claeskens

& Jansen, 2015) and number of clusters were not specified in advance. The average silhouette measure = 0.60 (i.e., a measure of cluster cohesion and separation) indicated good cluster quality for the two clusters, as shown in Figure 1 and Table 3. Subgroup A (*n* =29; 53.7%) demonstrated FFT impairments and so were termed Magnocellular-Deficit Dyslexics (MD-Dyslexics), while Subgroup B (*n* =25; 46.3%), who demonstrated unimpaired FFTs, were labelled Magnocellular-Typical Dyslexics (MT-Dyslexics). Overall, the low contrast (5% modulation) task was found to be the most discriminative predictor of cluster membership.

Results of the subsequent ANOVAs show the two dyslexic subgroups did not differ in age or nonverbal intelligence, nor text reading, phonological awareness nor rapid naming measures, confirming that the identified clusters were not an artifact of known factors (See Table 3). Rather, MD-Dyslexics were specifically characterized by significantly lower temporal thresholds (i.e., slower temporal processing) across FFT for both contrast modulation tasks compared with MT-Dyslexics and neurotypical children. In contrast, MT-Dyslexics demonstrated temporal thresholds that were equivalent to the neurotypical children at both contrast modulations, though their reading, rapid naming scores and phonological awareness were significantly reduced.

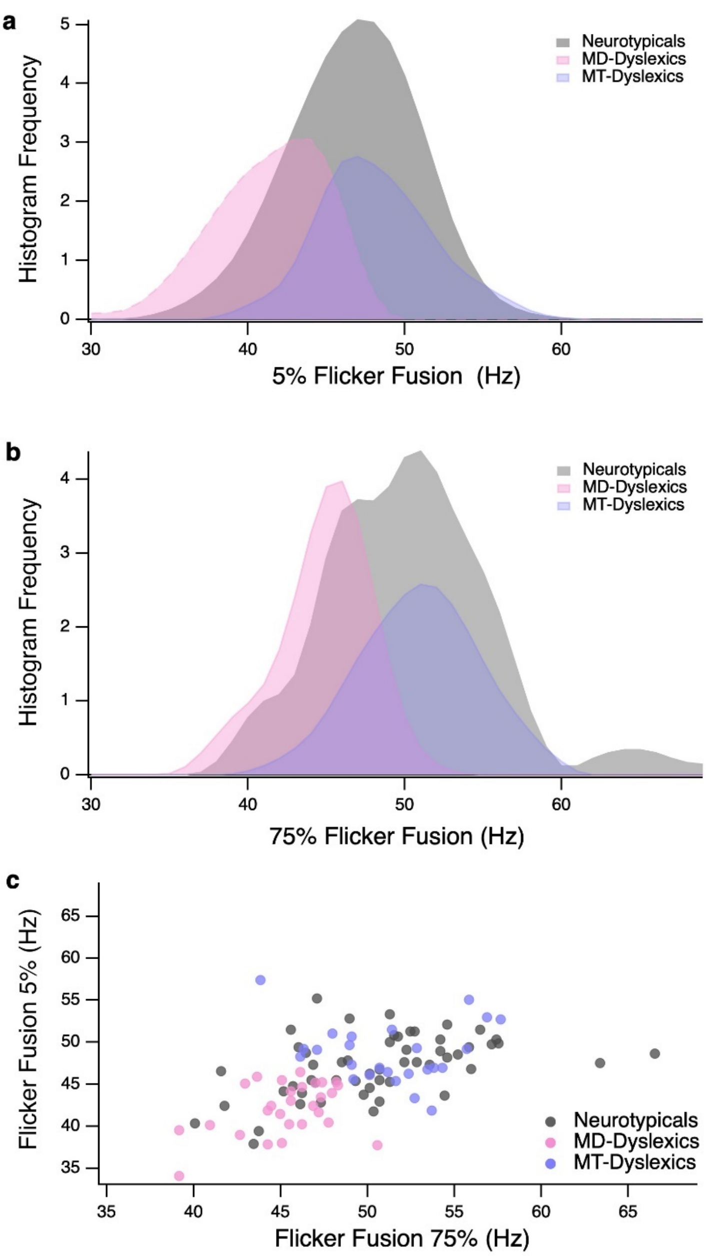

Figure 1. Flicker Fusion Threshold (FFT) Distribution of the Dyslexic Subgroups identified via Cluster Analysis and of the Neurotypicals.

Note. Frequency Distributions of Subgroup A ('Magnocellular-Deficit Dyslexics'), Subgroup B (Magnocellular-Typical Dyslexics') and Neurotypicals for (a) the Low Contrast (5%) FFT Task; and (b) the High Contrast (75%) FFT Task. (c) Scatterplot of Low and High Contrast FFT Performance of the identified Dyslexic Clusters and Neurotypicals. Neurotypicals have been included in Figure 1a and 1b for comparative purposes and were not included in the cluster analysis.

Table 3. *Comparison of Neurotypical and Dyslexic Subgroups for Flicker Fusion, Age, Nonverbal Intelligence, and Reading Measures*

	a. MD-Dyslexics *n* = 29		b. MT-Dyslexics *n* = 25		c. Neurotypical Children *n* = 54		*F*			
	M (SD)	Range	*M (SD)*	range	*M (SD)*	range	(2, 105)	*p*	*d*	Tukey HSD Post hoc
75% FFT	45.38 (2.66)	39.17-50.57	51.29 (3.54)	43.85-57.68	50.42 (4.57)	40.09-59.68	19.46	<.001	1.22	a< b**, a< c**, b = c
5% FFT	41.94 (3.23)	34.12-46.45	48.56 (3.31)	41.88-55.09	47.20 (3.64)	37.93-55.21	30.04	<.001	1.51	a< c**, a< c**, b = c
Age	9.96 (1.20)	8.00-12.25	10.34 (1.20)	8.08-12.92	9.86 (1.13)	8.00–12.17	1.46	.237	0.33	-
Nonverbal Intelligence	103.66 (8.87)	88-121	105.48 (6.96)	89-118	106.70 (10.19)	85-121	1.04	.357	0.28	-
Reading Accuracy	77.32 (9.15)	69-99	76.80 (6.27)	69-90	100.74 (10.25)	80-120	88.78	<.001	2.61	a< c**, b< c**, a = b
Reading Rate	74.56 (7.44)	69-90	76.44 (7.29)	69-90	99.96 (9.89)	80-124	103.96	<.001	2.84	a< c**, b< c**, a = b
Reading Comprehension	87.96 (14.45)	69-117	94.04 (12.50)	69-113	104.72 (11.80)	81-131	17.53	<.001	1.16	a< c**, b< c*, a = b
Phonological Awareness	87.81 (12.67)	70-116	87.20 (10.61)	70-110	103.33 (11.16)	85-125	25.34	<.001	1.40	a< c**, b< c**, a = b
Rapid Naming	82.78 (12.03)	61-104	84.00 (9.31)	69-104	95.26 (12.41)	69-118	13.59	<.001	1.04	a< c**, b< c**, a = b

Note. To account for the multiple comparisons, a Bonferroni adjustment to the alpha level (p = .006) was applied; Cohen's $d \geq 0.2$, $d \geq 0.5$, and $d \geq 0.8$, represent small, medium, and large effect sizes, respectively; FFT scores are reported in hertz; all neuropsychological measures are reported as Standard Scores. For post-hoc analyses *p < .05, ** p < .001.

4.4.4 Are Temporal Processing Deficits associated with Previously Described Subtypes of Dyslexia?

The total dyslexic sample (*N* =54) was classified into four subtypes based on performances at least 1 *SD* below age expectations on either the rapid naming composite (Naming Speed Deficit; *n*=12), elision task (Phonological Deficit; *n*=10), both tasks (Double-Deficit; *n*=18), or neither task (No-Deficit; *n*=14) according to criteria provided by Wolf and Bowers (1999). This permitted investigation to determine if these subtype classifications could predict those dyslexic participants identified with and without temporal processing impairments (i.e., FFT deficit) in the cluster analysis. Subtype classification was then confirmed via ANOVA (see Supplementary Information), and the presence (or absence) of a temporal processing deficit, based on the results of the cluster analysis, was entered as the dependent variable. The results of a direct logistic regression were not significant, χ^2 (3, *N* = 54) = 4.88, $p = .181$, indicating that temporal processing impairments per se are not specifically associated with the subtypes proposed by the Double-Deficit Hypothesis (See also Supplementary Table S2 and 3).

4.4.5 How do Temporal Visual Processing Thresholds relate to Reading Skills?

As shown in Table 4, one-tailed Pearson correlational analyses revealed that better performance on the high contrast FFT task correlated significantly with better low contrast FFT, nonverbal intelligence, reading accuracy, reading rate, phonological awareness, and rapid naming performances in neurotypical children.

Table 4. *Correlations Between Reading Skills and Flicker Fusion Thresholds for Each Group*

	a. MD-Dyslexics n = 29		b. MT-Dyslexics n = 25		c. Neurotypicals n = 54	
	5% FFT (M=41.94)	75% FFT (M=45.38)	5% FFT (M=48.56)	75% FFT (M=51.29)	5% FFT (M=47.20)	75% FFT (M=50.42)
5% FFT	-	.415*	-	.177	-	.498**
Nonverbal Intelligence	-.025	.161	.477**	0.26	.162	.287*
Reading Accuracy	.182	.365*	.025	-.111	.122	.435**
Reading Rate	.343*	.337*	-.542**	.083	.053	.349**
Reading Comprehension	.278	-.158	.244	-.230	.092	.082
Phonological Awareness	.326*	.616**	.364*	.422*	.172	.429**
Rapid Naming	.313	.334*	-.313	-.304	.127	.284*

Note. *$p < .05$, ** $p < .01$; According to Cohen's guidelines, $r \geq 0.10$, $r \geq 0.30$, and $r \geq 0.50$, represent small, medium, and large effect sizes, respectively (Cohen, 1988); standard scores used for all clinical tasks. FFTs are reported in Hz.

MD-Dyslexics showed a similar pattern of correlations, with high contrast FFT also correlating positively with low contrast FFT, reading accuracy, rate, phonological awareness and rapid naming performances, and low contrast FFT positively correlating with reading rate and phonological awareness. In the MT-Dyslexic subgroup, high and low contrast FFTs also positively correlated with phonological awareness, while low contrast FFT also correlated positively with nonverbal intelligence. Moreover, MT-Dyslexics, in contrast to MD-Dyslexics, showed a negative correlation between 5% FFT and reading rate. The difference in correlations between MT and MD subgroups, tested by applying Fisher's transformation between the groups for FFT 5% and reading rate, showed a significant difference (Z = 3.33, p = .0009, two-tailed).

MT-Dyslexics also showed a negative trend in the relationship between FFTs and rapid naming. Scatterplots for phonological awareness, rapid naming, and reading rate are shown in Figure 2. They indicate that the correlational differences reported between the two dyslexic subgroups are not due to difference in range of performances on phonological awareness, rapid naming and reading rate.

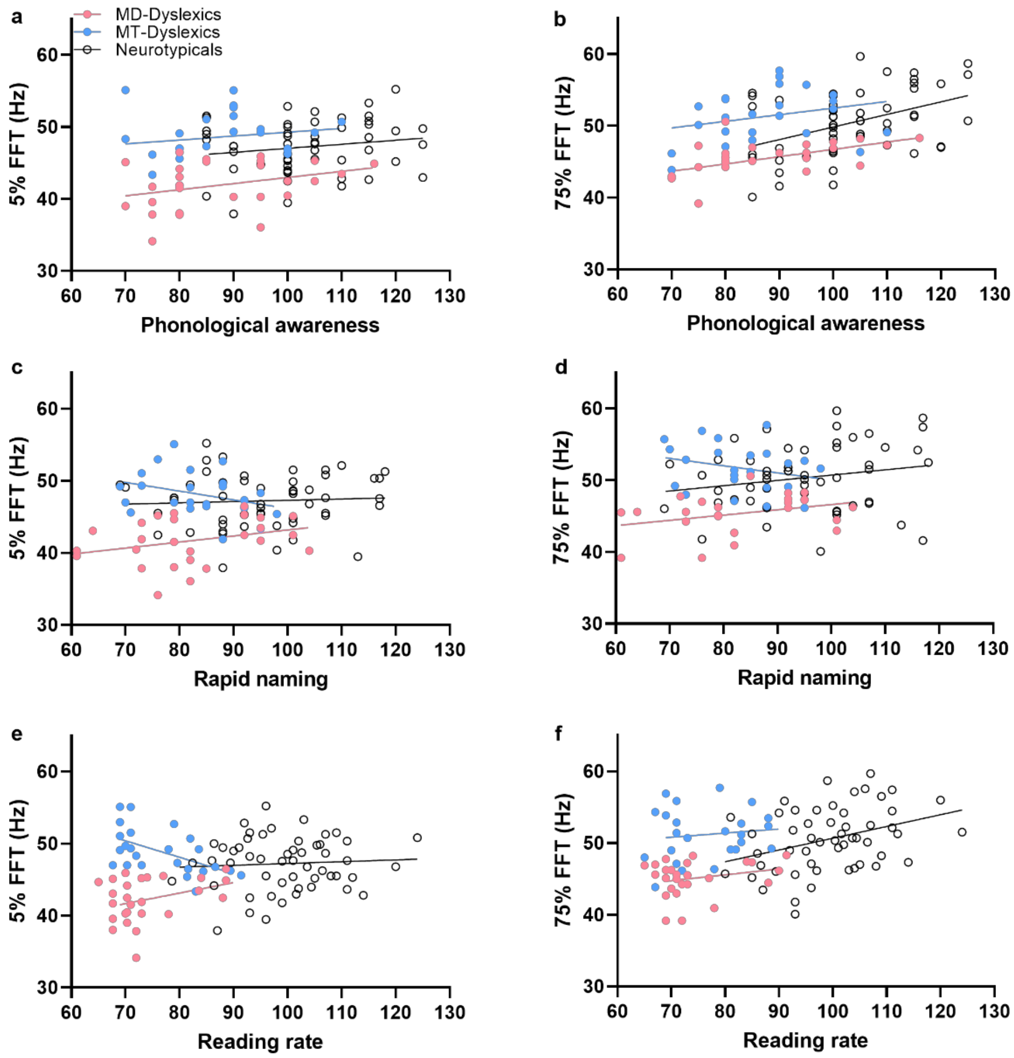

Figure 2. Correlations between Flicker Fusion Thresholds (FFTs) and Reading Measures.

Note. Correlations between Low Contrast (5%) FFTs and (a) Phonological Awareness; (c) Rapid Naming; (d) Reading Rate; and High Contrast (75%) FFTs with (b) Phonological Awareness; (d) Rapid Naming; (f) Reading Rate.

4.4.6 Is FFT a Valid Clinical Identifier of Dyslexic Children with Temporal Deficits?

Results of a second discriminant analysis showed that FFTs significantly differentiated the MD-Dyslexic subgroup from the neurotypical children, $\lambda = .631$, $\chi^2(2) = 36.411$, $p < .001$, canonical $R^2 = .370$, with both the high contrast ($r = .786$)

and low contrast (*r* = .916) loading highly onto the discriminate function. Overall, the model showed strong classification accuracy (79.3%), with 82.14% (sensitivity) of MD-Dyslexics and 77.78% (specificity) of neurotypicals accurately classified.

4.5 Discussion

Thresholds of temporal processing have rarely been used to explore the Magnocellular Deficit Theory of Dyslexia, despite strong evidence indicating that the M stream is best isolated by its fast firing recovery rates, rather than just contrast and spatial properties (Brown et al., 2018; Bullier et al., 1996; Klistorner et al., 1997; Livingstone et al., 1991; Merigan & Maunsell, 1990; Schiller et al., 1990). Thus, the current study investigated temporal processing thresholds of dyslexic and typical children using FFTs, at both low and high contrast, to comprehensively establish a magnocellular-temporo-spatial test that could be utilized clinically.

Our findings extend on those from previous FFT studies of dyslexia (Brown et al., 2020; Chase & Jenner, 1993; McLean et al., 2011; Talcott et al., 1998) by showing significant heterogeneity in dyslexic FFT performances and, more importantly, establishing the presence of two distinct subgroups – one characterized by impaired magnocellular-temporal processing thresholds (MD-Dyslexics) and the other by threshold levels equivalent to those of neurotypicals (MT-Dyslexics). The finding that 53.7% of the dyslexic sample were classified as MD-Dyslexics is comparable with the prevalence reported for phonological (47-62%) and rapid naming (19-44%) subtypes of dyslexia (O'Brien et al., 2012). Although no previous FFT study has analysed the presence of dyslexic subgroups with and without temporal deficits, research from our lab has shown that 43-50% of dyslexic children demonstrated FFTs 1 *SD* below matched controls (Brown et al., 2020). Similarly, McLean et al. (2011) identified that 42.5% of their dyslexic children performed 1 *SD* below matched controls on M-based temporal thresholds. Together, the consistency of these findings suggests that almost half of dyslexic individuals are likely to be characterised by magnocellular-temporal processing impairments.

Our results indicate that the presence of temporal processing impairments are not necessarily related to the phonological, rapid naming, double-deficit, or no-deficit subtypes of dyslexia that are proposed by Wolf and Bowers' Double-Deficit Hypothesis (Wolf & Bowers, 1999) and so provide evidence for the identification of a new subgroup of dyslexia characterised by visual temporal processing differences. Our results compliment the findings of several studies showing little association between tests of M functioning and specific subtypes of dyslexia (Ridder, Borsting, & Banton, 2001; Williams, Stuart, Castles, & McAnally, 2003), however, others studies have reported a link between M functioning and phonological and double-deficit subtypes (Borsting et al., 1996; Ridder, Borsting, Cooper, McNeel, & Huang, 1997; Slaghuis & Ryan, 1999; Spinelli et al., 1997), indicating a clear need for further research. Inclusion of orthographic processing tasks, for example, would enable future FFT research to further explore dyseidetic and surface subtypes(Boder, 1970; Castles & Coltheart, 1993).

The MD-Dyslexic and neurotypical groups showed similar correlation patterns. FFT performance, particularly high contrast FFT, was related to performance in almost all reading measures assessed (reading accuracy and rate, phonological awareness, rapid naming, but not reading comprehension). By comparison, the FFTs of MT-Dyslexics showed a different relationship pattern with reading skills: 5% contrast FFT was negatively related to reading rate (i.e., speed); there were also non-significant negative trends between FFTs and rapid naming, a task also reliant on speed. However, like the other two groups, FFTs of the MT-Dyslexics correlated with phonological awareness. This is consistent with several other papers that show a relationship between M functioning and phonological skills (Au & Lovegrove, 2001; Cestnick & Coltheart, 1999; Talcott et al., 1998; Tallal, 1980; Tallal, Miller, & Fitch, 1993; Witton et al., 1998). While it is not fully clear what other factors differentially characterise MD-Dyslexics and MT-Dyslexics, several possibilities can be speculated from the current findings. Reading rate and low contrast temporal processing were positively related in MD-Dyslexics, but negatively related in MT-Dyslexics. This dissociation was statistically significant and provides novel evidence indicative of a relationship between temporal processing speed and reading speed. For MT-Dyslexics, despite efficient temporal processing speed, performance on speed-based measures (i.e., reading rate and naming speed) are likely to be related to additional factors not measured in the current study, such as speed of articulation, automaticity in accessing the multiple cognitive processes required by both tasks, and other cognitive processes, including working memory.

In the current study, MD-Dyslexics demonstrated flicker frequency thresholds that were on average 10-13% (~5-6 Hz) lower than MT-Dyslexics and neurotypicals (as shown in Table 3). Reduced FFT performance can be used to discriminate MD-Dyslexics from neurotypical populations with good sensitivity (82.14%) and specificity (77.78%). Although the clinical significance of a specific M-based temporo-spatial psychophysical task has rarely been considered in past research, similar classification accuracy was reported for adult dyslexics by Talcott et al. (1998), as shown in Supplementary Table S1. Our results provide initial evidence for the clinical applicability of FFT tasks as reliable measures of magnocellular-temporal efficiency that could be used to aid assessment and diagnosis of one subgroup of dyslexia. As interventions that target other properties of the M stream (i.e., motion and contrast) show strong efficacy in improving aspects of reading, and in particular reading rate (Holloway, Náñez, & McBeath, 2017; Peters, De Losa, Bavin, & Crewther, 2019), future research should also consider evaluating the utility of FFT and other temporal processing training programs for dyslexia.

In summary, the findings of the current study establish that a subgroup of dyslexic children (MD-Dyslexics) are specifically characterized by a significant impairment in magnocellular-temporal processing thresholds. The presence of this temporal impairment was not better categorized by the presence or absence of phonological awareness and/or rapid naming impairments as is commonly used to classify dyslexic subtypes in past research. It was also not an artifact of differences in age, nonverbal intelligence, nor severity or pattern of reading impairments between the MD-Dyslexic and MT-Dyslexic subgroups as they were comparable on reading, phonological awareness and rapid naming performances. Rather, for MD-Dyslexics, poorer FFTs, particularly high contrast FFT, was related to worse reading accuracy, reading rate, phonological awareness and rapid naming outcomes. In contrast, the FFTs of MT-Dyslexics were much less related to reading outcomes. Thus, we propose that temporal processing impairments characterize a previously unidentified subtype of dyslexia. This subtype can be easily identified using FFT tasks with good clinical accuracy (79.3%). FFTs tasks should therefore be considered as a valid non-invasive test of magnocellular temporal efficiency for dyslexia, that could be clinically used to assist diagnosis and appropriate treatment recommendations. FFT tasks could also prove useful in identifying pre-reading children at risk of developing dyslexia, though further research is required.

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4.7 Author Contribution Statement

JP, EB and SC designed the experiment, and EB and SC supervised the project. DC built the psychophysical task. JP and AB performed the experiment. JP analysed data and wrote the manuscript, with all other authors contributing to the drafting of the manuscript. All authors reviewed the manuscript.

4.8 Additional Information

4.8.1 Supplementary Information

Supplementary information accompanies this paper.

4.8.2 Funding

None.

4.8.3 Competing Interests

The authors declare no competing interests.

4.8.4 Data Availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

4.9 References

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CHAPTER 5

Eye Movements During RAN as an Operationalization of the RAN-Reading "Microcosm"

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The published version of this paper is provided in Appendix J.

5.1 Abstract

Rapid Automatized Naming (RAN) is a strong predictor of reading aloud, though there is little agreement on what underpins RAN or how it relates to reading. Some theorize phonological skills, while others suggest that RAN reflects the 'microcosm' of cognitive and attentional processes also required for reading, with more recent research using eye movements in an attempt to study this relationship. In the current study we aimed to extend on previous investigations to identify whether the temporal patterns of eye movements predict RAN and can therefore be established as a method to study the cognitive processes underlying RAN that could then be utilized to elucidate the relationship of RAN to reading. A Gazepoint eye tracker was used to record the eye movements of 93 learner readers aged 5-8 years (*M* age = 7.00) while performing a custom computerized alphabetic RAN task. Text reading accuracy, comprehension and rate; nonverbal intelligence; and phonological awareness abilities were also assessed. Regression analyses showed that, independently of phonological awareness, eye movements (fixation count and fixation duration) measured during RAN tasks were highly reflective of children's rapid naming performance (92.8%). Both mean fixation count and mean fixation duration during RAN tasks also predicted text reading accuracy (36.3%), comprehension (31.6%), and rate (36.2%) scores, and in predicting these text reading skills there was a high level of shared variance with RAN performance. In a sub-sample of participants, longer average fixation durations and counts independently discriminated children with reading difficulties (*n* = 18; aged 7-9) from neurotypical children matched for age (*n* = 18), but not from younger neurotypical children matched for reading level (*n* = 18; aged 5-6). Together, these results suggest that the analysis of eye movements recorded during RAN allows for the operationalization of many of the spatially and temporally-bound cognitive and attentional processes that underpin the RAN, and a step towards elucidating its relationship to reading.

5.2 Introduction

Rapid Automatic Naming (RAN) is commonly used to measure the ability to rapidly, accurately, and sequentially name a series of repetitive and familiar visual stimuli (i.e., pictures, colours, letters or digits; Denckla & Rudel, 1974). RAN tasks are also known to successfully differentiate those individuals with and those without diagnosed reading difficulties (i.e., specific learning disorder in reading, developmental dyslexia; Denckla & Rudel, 1974). However, until the last few years there has been little consensus about how RAN relates to reading (for a review, see Kirby, Georgiou, Martinussen, & Parrila, 2010), Indeed, early interpretation of the RAN-reading relationship was associated with an impaired ability to make adequate visual to verbal conversions (letter-sound conversions) during RAN and reading, thus limiting the automaticity of access to the phonological representation and impairing task performance (Clarke, Hulme, & Snowling, 2005; Savage, Pillay, & Melidona, 2007; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; Vukovic & Siegel, 2006; Ziegler et al., 2010). A second common interpretation has been that RAN reflects more a microcosm of the multiple cognitive and attentional skills required for reading (Denckla, 1988), which must take place in the context of sequentially organized eye movements. Recent studies have attempted to elucidate these hypotheses by investigating the individual differences in eye movements as a means to identify which cognitive processes may contribute to RAN (Al Dahhan et al., 2014; Al Dahhan, Kirby, Brien, & Munoz, 2016a; Jones, Ashby, & Branigan, 2013; Jones, Branigan, Hatzidaki, & Obregón, 2010; Jones, Obregón, Kelly, & Branigan, 2008; Pan, Yan, Laubrock, Shu, & Kliegl, 2013; Yan, Pan, Laubrock, Kliegl, & Shu, 2013). However, whether eye movements during RAN are reflective of, and hence predictive of overall RAN performance has not yet been fully elucidated. If indeed the eye movement characteristics are not strong predictors, then using gaze technology to study cognitive processing during RAN would be theoretically uninformative. Thus, the current study aimed to first establish whether RAN performance is dependent on the mean duration and number of fixations needed to name each RAN stimuli, which should lead to confirmation that eye movements can be used to operationalize and measure the time needed to accomplish the cognitive and attentional processes that underpin RAN. Such understanding of the time constraints needed for successful familiar object recognition and verbalization during RAN will add information to how RAN is related to reading fluency and why those with reading difficulties often perform poorly on RAN tasks.

Much of the earliest work relating eye movements and cognitive demands in tasks related to reading was pioneered by Rayner (1998). For example, fixations are longer and saccade sizes are shorter during oral reading as compared to silent reading (Kim, Petscher, & Vorstius, 2019; Rayner, 1998), while saccades, regressions, and fixation durations increase with greater visual/orthographic similarity during RAN (Al Dahhan et al., 2016a). Recent research has also shown that individual differences in temporally-based fixation durations are indicative of duration of attentional engagement related to speed of visual, symbolic, and orthographic processing and potentially include time to access the lexicon and verbalize the stimuli (Eckstein, Guerra-Carrillo, Miller Singley, & Bunge, 2017; Kim et al., 2019). Mean fixation counts per stimuli have been suggested to measure spatial distribution of attention indicative of the amount of visual information processed in each fixation (Goldberg & Kotval, 1999; Holland & Komogortsev, 2011; Rayner, Ardoin, & Binder, 2013), while saccade duration, a measure dependent on speed of activation and time to move to the spatial location of the next stimuli to be attended (Baloh, Sills, Kumley, &

Honrubia, 1975), may provide insights into the cognitive processes that take place between fixations during RAN and reading. Neural networks associated with eye movement control and attention are similarly activated in both RAN and reading (i.e., the ‘reading network’; Misra, Katzir, Wolf, & Poldrack, 2004), leading to the suggestion that RAN could be considered as a surrogate measure of the efficiency of this ‘reading network’ (Al Dahhan, Kirby, & Munoz, 2016b), and that eye movements could provide insight into the cognitive and attentional processes important to both RAN and reading.

Furthermore, children and adults diagnosed with a reading disorder are consistently reported to display less efficient patterns of eye movements during RAN and reading tasks, i.e., smaller perceptual spans, longer and more fixations per word, shorter saccades, and more regressions when compared with age-matched typical readers (Al Dahhan et al., 2014; Al Dahhan et al., 2016a; Ashby & Rayner, 2004; Hawelka, Gagl, & Wimmer, 2010; Henry, Van Dyke, Kuperman, & Writing, 2018; Jones et al., 2010; Jones et al., 2008; Kuperman, Van Dyke, & Henry, 2016; Logan, 2009; Moll & Jones, 2013; Pan et al., 2013; Rayner, 1986; Yan et al., 2013). Such differences in gaze patterns have been interpreted to reflect that those with reading difficulties require more attentional resources and time to attend and engage cognitive mechanisms in order to process information during fixations than normal age matched readers. However, while many now argue that eye movements can be used to investigate the cognitive processes involved in RAN and reading (Al Dahhan et al., 2016b; Eckstein et al., 2017; Kim et al., 2019), there is only limited research specifically exploring how well RAN eye movements predict RAN performance or reading outcomes. Establishing this would aid in confirming that using eye movements to study cognitive processing during RAN is useful in understanding the RAN-reading relationship.

Currently we are only aware of two studies by Al Dahhan et al. (2014), that have reported on the extent to which eye movements recorded during RAN may predict single word reading and RAN performance. Al Dahhan et al. (2014) found that fixation duration and count recorded during RAN significantly predicted reading in adults, while Al Dahhan et al. (2016a) demonstrated that fixation duration during rapid naming, predicted reading and RAN performance in children (aged 6-7 and 9-10) and concluded that RAN and reading are related via eye movements which reflect the time required to extract and process stimulus information. While the aims of both papers were to investigate the predominant theories of RAN via visual and phonological manipulation of RAN tasks, rather than investigate the role of eye movements, these previous results provide impetus for further investigations to establish such a role for text reading (Araújo, Reis, Petersson, & Faísca, 2015; Papadopoulos, Spanoudis, & Georgiou, 2016) rather than single word reading as used by Al Dahhan et al. (2014; 2016a). The close relationship known between RAN and oral text reading is presumably because both skills draw on similar cognitive processes of visual stimulus identification and rapid sequential processing (Araújo et al., 2015; Papadopoulos et al., 2016) – skills less required for single word reading lists. This would suggest that RAN-based eye movements are likely to be more predictive of text reading skills as compared with single word reading, necessitating the current study.

Thus, in the current study we aimed to extend upon the works of Al Dahhan et al. (2014; 2016a) to further clarify two aspects regarding the role of eye movements during RAN as a way to measure the RAN-reading cognitive ‘microcosm’. A serial alphabetic RAN task was chosen because this type of RAN task most strongly predicts single reading across development (van den Bos et al., 2002). The first aim was the role of eye movements during a serial alphabetic RAN task, and their relationship to RAN and oral text reading performance. We investigated this in a broad sample of primary school-aged learner readers by:

1. examining how well eye movements recorded during RAN predict RAN performance;
2. examining the extent with which eye movements and phonological awareness separately predicted RAN, to demonstrate whether RAN is more reflective of phonological processes or the cognitive 'microcosm' eye movements are believed to reflect;
3. determining the unique contribution of RAN-based eye movements in predicting text reading accuracy, rate and comprehension performances and;
4. identifying the shared contributions between RAN and RAN-based eye movements as overlapping predictors of text reading performances, in order to further establish that eye movements can be utilized as proxy measures of RAN and as a means of identifying the microcosm of cognitive processes that underly RAN and the RAN-reading relationship.

The second focus was on discriminating reading difficulties using eye movements, and in this aspect of the research we aimed to:

5. identify whether eye movements during RAN discriminate children with reading difficulties from chronological- and reading-age matched normal readers, which would further indicate that eye movements are useful measures of the cognitive processing underpinning reading development.

Based on the findings of previous research, we hypothesized that eye movement patterns during RAN would prove highly reflective of RAN performance, so would strongly predict RAN performance, and to a greater extent than phonological awareness. It was also hypothesized that eye movements during RAN would significantly predict text reading performances (accuracy, comprehension, and rate) more strongly than for the single words as used by Al Dahhan et al. (2014; 2016a), and that the predictive contribution of RAN eye movements on text reading would largely overlap with the contribution provided by RAN performance. It was also hypothesized that eye movements would successfully differentiate children with reading difficulties from chronological-, and reading-age matched normal readers, providing further evidence that individual differences in eye movements are related to both RAN performance and the cognitive processes involved.

5.3 Method

5.3.1 Participants

For the first part of the study, ninety-three primary school children (52 male) aged five years to nine years two months (mean age = 7.00, *SD* = 0.99), from Prep (i.e., the first year of formal schooling; *n* = 32), Grade 1 (*n* = 35), and Grade 2 (*n* = 26) participated in the study. Participants were tested towards the end of the school year to ensure that children in Prep had received close to one year of formal instruction of word and sentence reading. Participants were recruited from mainstream primary schools and an extracurricular program for children with diagnosed specific reading disorders to ensure the sample was representative of the full reading spectrum. All participants had normal intelligence (Standard score ≥85 for age), normal or corrected-to-normal vision and hearing, and English as their primary language. The sample included twenty-three participants diagnosed with specific reading difficulties (i.e., specific learning disorder in reading and/or developmental dyslexia), which was confirmed via standardized assessment (Reading performance >1.5 *SD* below age norms; American Psychiatric Association, 2013; O'Brien, Wolf, & Levett, 2012). Children with known medical and neurodevelopmental disorders other than developmental dyslexia or specific reading disorder were excluded (see DSM-5; American Psychiatric Association, 2013). Table 1 provides descriptive statistics for all measures of interest.

Table 1. *Participants Means and Standard Deviations for Reading Related Measures and Eye Movements*

	M	*SD*	Min.	Max.
RCPM	115.96	9.45	91.00	125.00
Phonological Awareness	104.16	15.27	70.00	145.00
RAN (raw score)	72.77	20.79	19.00	113.00
Reading Accuracy	99.46	18.10	65.00	135.00
Reading Comprehension	94.99	16.55	65.00	131.00
Reading Rate	103.75	19.70	65.00	145.00
Fixation Duration (ms)	442.37	71.50	270.22	510.00
Fixation Count	1.71	0.35	1.13	2.52
Saccade Duration (ms)	54.64	21.49	20.03	100.00

Note. Reading, phonological awareness, and RCPM means and *SD*'s represent standard scores; ms = milliseconds. RCPM = Ravens Color Progressive Matrices.

For the second part of the study, a sub-sample of the recruited participants (n = 54) were further investigated in order to compare the eye movement patterns of those with and without reading difficulties. Children with reading difficulties (RD; aged 7-9; n = 18) were compared to chronological-age controls (CA; aged 7-9; n = 18) and reading-age controls (RA; aged 5-6; n = 18). RD children were one-to-one matched with both control counterparts (CA and RA) on age-standardised nonverbal intelligence ($z = \pm 0.8$), with CA children within 1 year of age, and with RA children within 1 year of reading age. An a priori power analysis indicated that this sample size was sufficient to detect a large effect size with 95% power.

5.3.2 Procedure

The research was carried out in accordance with ethics approval granted by the La Trobe University Faculty Human Ethics Committee and the Victorian State Department of Education. Parents of participants were required to provide written informed consent for their child to engage in the study. All children voluntarily participated. Testing occurred in a small quiet room, over approximately two 30-minute sessions at the participants' school or program, with tasks administered in randomized order.

5.2.3 Materials

5.2.3.1 Nonverbal intellect.

The Raven's Colored Progressive Matrices (RCPM) test was used to assess nonverbal reasoning (Raven, Court, & Raven, 1998). The RCPM contains three series of 12 matrices of increasing complexity. Standard scores were calculated based on chronological age using normative data provided in Cotton et al. (2005). The RCPM is standardized in a range of countries including Australia and is considered appropriate for children of ages five to eleven years and for children with reading difficulties (Cotton et al., 2005). The Raven's exhibits good test-retest reliability ($r = .80$) (Raven et al., 1998) and high internal consistency ($\alpha = .89$), with minimal variation across age (Cotton et al., 2005).

5.2.3.2 Reading ability.

Reading was measured with the Neale Analysis of Reading Ability – Third Edition, which is a standardized test of reading ability for children in Grades Prep to 6, commonly used in Australian school settings (Neale, 1999). The test measures reading accuracy, comprehension and rate during prose oral reading via a series of up to six passages of increasing difficulty with accompanying questions. Children were first required to complete a practice passage, and all children were able to participate in the test. Grade-based standard scores for reading accuracy, comprehension and rate were calculated from the raw scores based on the manuals' normative data. Internal consistency results vary by age, with α ranging from .86 to .92 for comprehension, .91 to .97 for accuracy and .71 to .94 for rate (Neale, 1999). The overall measure has high content validity and face validity for the construct of reading aloud and is effective in discriminating between ages and differing reading abilities, including poor reading and dyslexia.

5.2.3.3 Phonological awareness.

Phonological knowledge was assessed using the Elision subtest, a sound deletion task, from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999). The age-based standard score was used as the measure of phonological awareness. It demonstrates good internal consistency (α =.91), test-retest (α = .82), and inter-rater reliability (r = .96), and has high concurrent validity with other tests of phonological processing (Wagner et al., 1999).

5.2.3.4 Rapid automatized naming.

The custom serial letter RAN task employed here consisted of 30 items of six randomly repeated letters (see Figure 1). RAN performance was recorded as number of stimuli named in 60 seconds, rather than time to complete, as used in most other

RAN tasks. A performance indicator of RAN that controlled for time was chosen as most of the eye movements variables included were time-based, while the 60 second time duration was selected to ensure that the averaged eye movement variables were representative. RAN tasks require stimuli to be named in a quick, automatic manner, so the uppercase letters A through F were chosen as stimuli because uppercase letters and letters from the beginning of the alphabet are learned earliest (Justice, Pence, Bowles, & Wiggins, 2006; McBride-Chang, 1999), so would be automatized earliest. Consistent with other alphabetic RAN tasks, each of the chosen stimuli were single-syllable. The task was presented as a single frame on a computer screen, and participants sat at a viewing distance of 60cm. The visual angle of each letter was 2 x 2 degrees. Participants were first provided a practice trial showing all six letter stimuli to ensure they could name each letter without error and to familiarize them with requirements of the task. Participants unable to accurately complete the practice trial were discontinued from the task. Participants were instructed to name aloud the stimuli as fast and as accurately as possible, from left to right, top to bottom, and repeating through the 30 stimuli as many times as possible, and self-correcting any errors, until the display disappeared (60 seconds). The total number of stimuli named was recorded manually. Eye tracking data was then analysed for the duration (60 seconds) of the task. Eye movements during naming errors were not removed from the data.

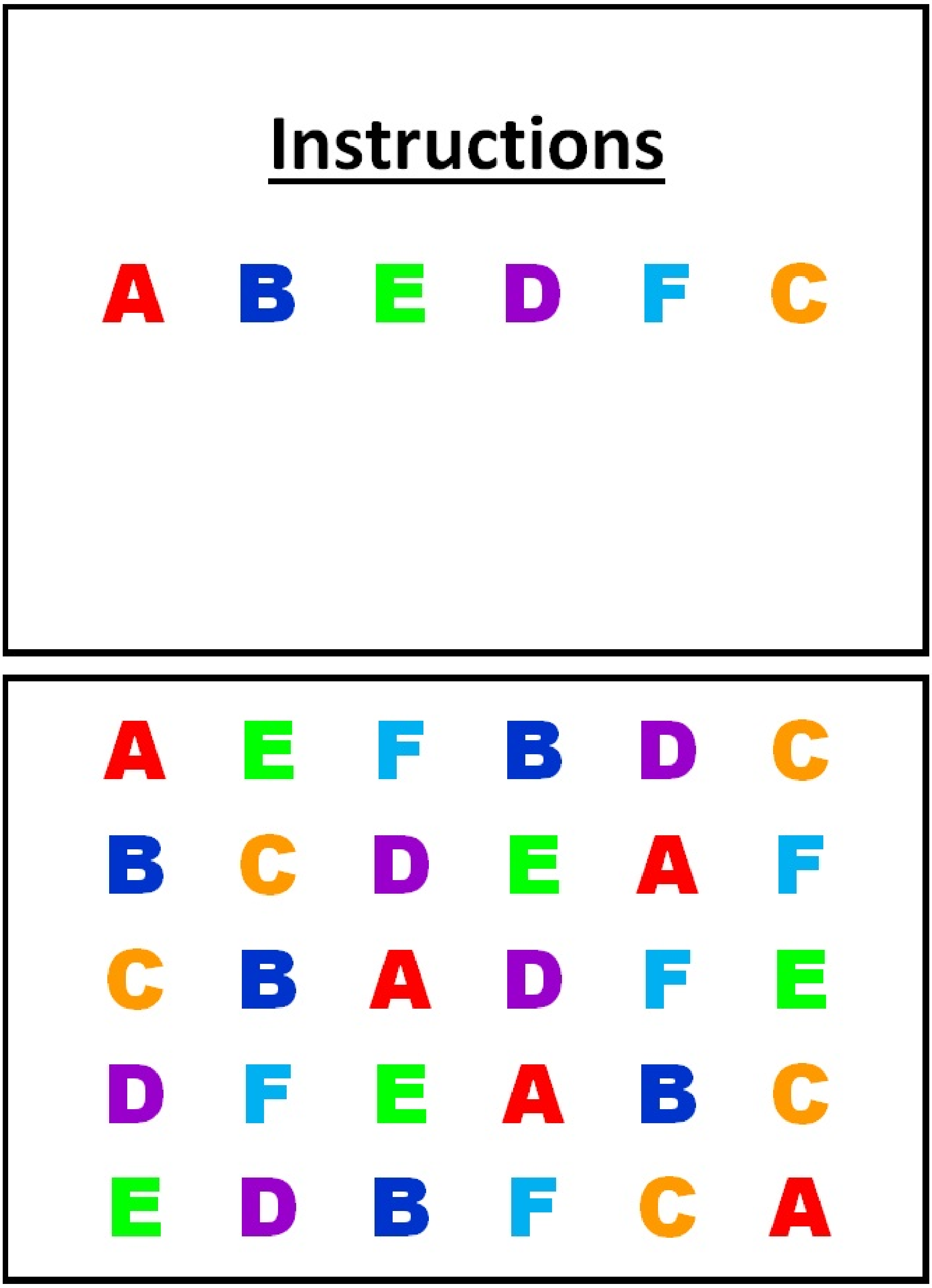

Figure 1. RAN Practice Trial (A); RAN Timed Trial (B).

5.2.3.5 Eye movement patterns.

Eye movements were recorded binocularly during the RAN task using a Gazepoint GP3 screen mounted infrared camera (60 Hz sampling rate; Gazepoint, www.gazept.com). The GP3 tracks vertical and horizontal eye positions with an average gaze position accuracy of 0.5 degrees. Participants were positioned 60 cm from the screen with their head placed in a chin and forehead rest to reduce movement. Before beginning the task, each participant underwent a 9-point eye movement calibration procedure. Fixation Duration (FD) was calculated as the average (mean) temporal length the fixations performed during the 60 second RAN task. Saccade Duration (ScD) was calculated as the average (mean) duration (in milliseconds) of saccades performed during the 60 second RAN task. This variable was chosen as it provides a summary measure of saccadic function (i.e., reflective of speed of activation and time required to move the eyes to the next fixation location) that permitted investigation of eye movements more broadly, while minimizing the number of variables included in analyses. Fixation Count (FC) was defined at the average number of fixations required per stimuli named and was calculated by dividing the total number of fixations made by the total number of letters named during the RAN task. As the RAN task used a fixed time limit rather than number of stimuli, the FC variable controls for individual participant RAN score differences (i.e., differences in number of letters named), and so is akin to fixation count measures used in experiments presenting a fixed number of stimuli.

5.3 Data Screening and Analysis

Data screening identified a total of twelve outliers across the eye movement measures (FD = 3; ScD = 6; FC = 3) that were just outside the normal distribution (i.e., ~4% of the eye movement data). To reduce this influence on parametric statistical analyses, outliers were pulled back to the next most extreme value within the normal distribution (Tabachnick & Fidell, 2013). Further assumption testing revealed no other violations.

Correlation analyses were conducted to determine which, if any, eye movement measures related to RAN and to inform which to include in the regressions. High correlations between the eye movements variables and RAN performance were found, suggestive of non-independence between the variables. This was not unexpected as the eye movements were recorded during the RAN task. Although multicollinearity between predictor variables is typically addressed by removal of one of those variables from the regression model, this was not performed in the current study given that multicollinearity has been shown to not reduce the reliability or predictive power of the regression model, rather only reducing the likelihood that individual predictors will be statistically significant (Allen, 2004). Therefore, a series of hierarchical multiple regressions was conducted to investigate what contribution eye movement patterns may make to RAN and to text reading ability (i.e., accuracy, comprehension, and rate) in young readers. The regression analysis for RAN included phonological awareness and the chosen eye movement variables to allow direct comparison of their contributions, and to identify whether RAN is more reflective of phonological processes or the cognitive 'microcosm' eye movements are believed to reflect. In each regression model for text reading (accuracy, rate, comprehension), the aim was to determine the unique contribution that eye movements provide to the reading skills, as well as the overlap in the contribution of eye movements and RAN, to reading. Other variables that are known to be important to reading, such as phonological awareness, were not included in the reading regressions as this has been previously investigated (see Al Dahhan et al., 2014). Eye movements were entered at step 1 to determine specifically what unique contribution they made independent of the broader RAN performance variable. RAN performances was then entered at step 2 to determine what further contribution RAN made to the reading models and how much variance contributed by eye movements and RAN was shared.

For the second part of our research, reading subgroups were compared using one-way analyses of variance (ANOVA's) to ascertain whether eye movements could differentiate between a group of children with reading difficulties, a matched group of chronological-aged normal readers, and a group matched on reading-age.

5.4 Results

5.4.1 The Relation of Eye Movements to Rapid Naming Performance and Reading

Pearson correlational results show that FD and FC correlated significantly with nonverbal intelligence, RAN, phonological awareness and all reading measures (see Table 2). Saccade Duration did not correlate with these measures.

Table 2. *Correlations between Rapid Naming, Reading, Phonological Awareness, Nonverbal Intelligence, and Eye Movement Patterns*

	2.	3.	4.	5.	6.	7.	8.	9.
1. RCPM	.311**	.448**	.321**	.335**	.235*	-.285**	-.250*	-.001
2. Rapid Naming	-	.377**	.642**	.600**	.613**	-.682**	-.874**	-.102
3. Phon. Awareness	-	-	.587**	.497**	.428**	-.307**	-.286**	-.065
4. Reading Accuracy	-	-	-	.831**	.823**	-.437**	-.540**	-.065
5. Reading Comp.	-	-	-	-	.729**	-.423**	-.494**	-.101
6. Reading Rate	-	-	-	-	-	-.502**	-.486**	-.019
7. Fixation Duration	-	-	-	-	-	-	.347**	-.272**
8. Fixation Count	-	-	-	-	-	-	-	.098
9. Saccade Duration	-	-	-	-	-	-	-	-

Note. *$p \leq .05$, **$p \leq .001$;
RCPM = Ravens Color Progressive Matrices; Phon. Awareness = phonological awareness.

5.4.2 Predictors of Rapid Naming

The independent eye movement variables, FC and FD, were chosen for the hierarchical multiple regression for RAN performance based on the significant correlations shown in Table 2. Phonological awareness was included based on past theoretical considerations of its importance to RAN. Therefore, phonological awareness, FD and FC were entered together as predictors of letter RAN performance.

The results in Table 3 show that only the two eye movement measures (FD and FC), and not phonological awareness, were significant predictors of RAN performance, together explaining 92.8% of the variance in the regression model. These results indicate that eye movements – namely shorter and fewer fixations made for each stimulus named – are highly predictive of rate of rapid naming performance in young readers, with more efficient eye movements relating to better performance outcomes and so should be considered as discrete substitute measures of RAN.

Table 3. *Predictive Contributions of Phonological Awareness and Eye Movement Patterns on Alphabetic Rapid Naming Performance*

Alphabetic Rapid Naming Performance	β	*r*	*sr*
Phonological Awareness	.04	.38	-.04
Fixation Duration	-.42**	-.68	-.38
Fixation Count	-.72**	-.87	-.66
Total R^2 = .928, F (3, 84) = 362.293, p <.001			

Note. *$p \leq .05$, ** $p \leq .001$; *According to Cohen's guidelines, r ≥.10, r ≥.30, and r ≥.50, represent small, medium, and large effect sizes, respectively* (Cohen, 1988).

5.4.3 Predictors of Reading Ability

Hierarchical multiple regressions were conducted for each text reading skill, despite the dependent variables (reading accuracy, comprehension and rate) being highly correlated (see Table 2), because the contributions of RAN-based eye movements to each of the three aspects of text reading is not fully known. For each analysis, FD and FC were entered as predictors at Step 1 to first establish the contribution of these discrete functions given their overlap with RAN as shown in the previous analyses, with RAN performance then entered at Step 2 to determine how much more variance it may contribute to the text reading analyses. Assumption testing revealed no violations. Table 4 presents the results of each reading regression (reading accuracy, comprehension, and rate) respectively.

Table 4. *Predictive Contributions of Eye Movement Patterns and RAN on Reading Accuracy, Reading Comprehension, and Reading Rate*

		Reading Accuracy			Reading Comprehension			Reading Rate		
		β	*r*	*sr*	β	*r*	*sr*	β	*r*	*sr*
Step 1:	Fixation Duration	-.28*	-.44	-.27	-.29*	-.42	-.19	-.38**	-.50	-.36
	Fixation Count	-.44**	-.54	-.41	-.40**	-.49	-.30	-.35**	-.49	-.33
		R^2 = .363**, *F* change (2, 89) = 25.34			R^2 = .316**, *F* change (2, 89) = 20.59			R^2 = .362**, *F* change (2, 859) = 24.12		
Step 2:	Fixation Duration	.08	-.44	.04	.07	-.42	.03	-.12	-.50	-.06
	Fixation Count	.17	-.54	.06	.20	-.49	.07	.09	-.49	.03
	Rapid Letter Naming	.84*	.64	.23	.82*	.60	.22	.61	.61	.17
		Change R^2 = .052*, *F* change (1, 88) = 7.87			Change R^2 = .049*, *F* change (1, 88) = 6.79			Change R^2 = .028, *F* change (1, 88) = 3.79		
		Total R^2 = .415**, *F* (3, 88) = 20.82			Total R^2 = .365**, *F* (3, 88) = 16.88			Total R^2 = .390**, *F* (3, 88) = 17.87		

Note. **p* ≤ .05, ** *p* ≤ .001; *According to Cohen's guidelines, r ≥.10, r ≥.30, and r ≥.50, represent small, medium, and large effect sizes, respectively* (Cohen, 1988).

The total variance explained by the reading accuracy regression model was 41.5%. FD and FC explained 36.3% of the variance at step 1, with RAN then explaining an additional 5.2% at step 2. The total reading comprehension analysis explained 36.5% of variance. FD and FC together explained 31.6% of the variance at step 1, and when entered at step 2, RAN performance explained an extra 4.9% of the variance. The total reading rate regression model explained 39.0% of the variance. At step 1, the two eye movement measures explained 36.2% of the variance, while RAN performance explained an extra 2.8% of the variance at step 2, although this was not a significant contribution.

However, when independent variables were considered separately the significance of eye movement measures no longer remained in any of the three final regression models. This is most likely due to the high level of overlap between RAN and the eye movement measures, as shown in the previous correlation and RAN regression analyses. In the final regression analyses for text reading, RAN was the only significant and individual predictor for Reading Accuracy and Comprehension, while no variable remained a significant unique predictor for Reading Rate.

5.4.4 Reading and Age Comparisons Between those with and without Reading Difficulties.

Results of initial group comparisons confirmed that the three groups were appropriately comparable. Preliminary analyses revealed no assumption violations. Raw scores for reading were used to facilitate comparisons during analyses; however standard scores and age-equivalents for reading have been provided in Table 5 to aid meaningful interpretation. Groups did not differ on age-standardized nonverbal intelligence (i.e., Raven's; F [2,50] = 0.42, p =.659, d = 0.25). The RD and CA groups did not differ in chronological age (F [2,50] = 44.05, p >.001, d = 2.65; Tukey HSD post-hoc comparisons showed only the RA group differed significantly from the RD and CA groups), while the RD and RA groups did not differ on reading age or phonological awareness, with only the CA group performing significantly better than the RD and RA groups (Reading accuracy, F [2,50] = 30.35, p <.001, d = 2.20; comprehension, F [2,50] = 28.23, p <.001; d = 2.24; rate, F [2,50] = 21.66, p <.001, d = 2.01), and phonological awareness, F [2,50] = 6.45, p =.003, d = 1.06). Statistically significant differences between groups for RAN performance were also found (F [2,50] = 8.08, p =.001, d = 1.14), with the CA group performing better than the RD group.

Table 5. *Participants Means and Standard Deviations for Age, Nonverbal Intelligence, and Reading Related Measures*

	Reading Disorder Group (*n* =18)		Chronological-age Group (*n* =18)		Reading-age Group (*n* =18)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Age in years	7.71	0.78	7.65	0.63	5.91	0.50
RCPM SS	107.72	10.13	110.52	6.88	109.11	9.71
RAN (raw score)	59.89	17.12	84.47	19.88	70.72	17.28
Phon. Awareness SS	87.35	7.09	107.00	14.24	102.35	11.06
Phon. Awareness Age Equiv	6.36	0.70	9.18	2.80	6.28	0.87
Reading Accuracy SS	75.00	8.08	110.35	12.16	102.44	6.50
Reading Accuracy Age Equiv	6.21	0.41	8.57	2.12	6.37	0.35
Reading Comprehension SS	77.55	11.71	101.00	13.63	94.89	11.81
Reading Comprehension Age Equiv	6.30	0.54	7.62	0.97	6.25	0.37
Reading Rate SS	80.83	13.66	118.07	15.15	104.88	12.45
Reading Rate Age-Equiv	6.63	1.13	10.00	2.38	6.72	0.87

Note. SS = Standard score; RCPM = Ravens Color Progressive Matrices; Phon. Awareness = phonological awareness; Age Equiv = age equivalent score

5.4.5 Comparisons of Eye Movements during Rapid Naming in Children with and without Reading Difficulties

One-way ANOVA comparisons of the eye movement patterns of children with reading difficulties, chronological-age matched controls and reading-age matched controls demonstrated statistically significant differences between groups for FD (F [2,50] = 3.90, p = .027, d = 0.80) and FC (F [2,50] = 4.66, p = .014, d = 0.87), with large effect sizes found. There were no differences between groups for ScD (F [2,50] = 2.45, p = .097, d = 0.63). Post-hoc comparisons using the Tukey HSD test indicated that the CA group differed significantly from the RD group in FD (414.30 vs 472.45 milliseconds) and FC (1.55 vs 1.89 fixations), with chronological-age-matched controls making more fixations on the RAN task with shorter average duration of fixations and fewer fixations per stimulus than those with reading difficulties. Neither group differed significantly from the reading-age-matched controls in FD (465.94 milliseconds) or FC (1.73 fixations). Figure 2 depicts performance of each reading group for Fixation Count (FC; Figure A), Fixation Duration (FD; Figure B), and Saccade Duration (ScD; Figure C).

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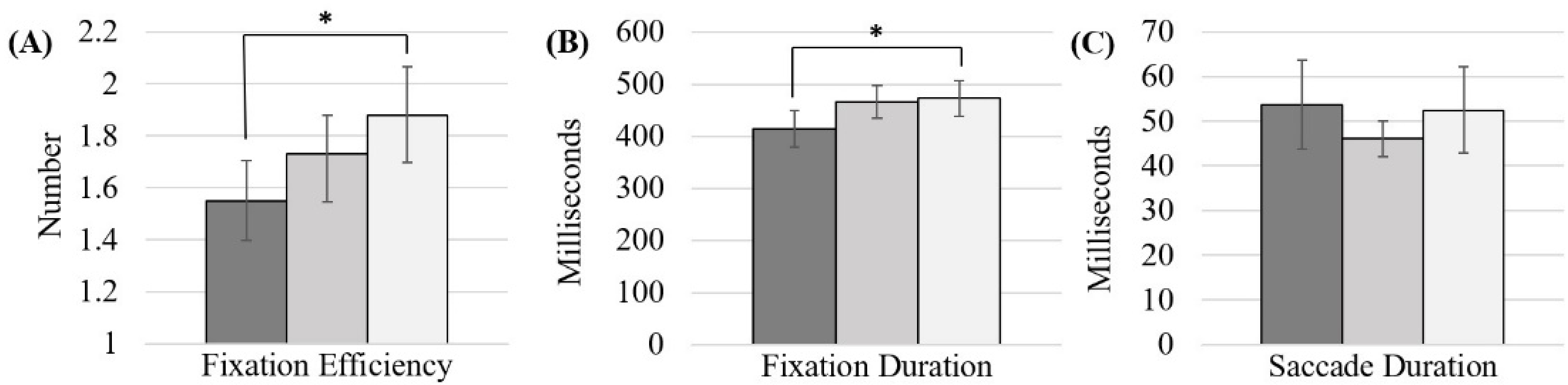

	Fixation Efficiency	Fixation Duration	Saccade Duration
CA controls (*n* = 18)	1.55 (0.29)	414.30 (68.11)	53.76 (18.56)
RA controls (*n* = 18)	1.73 (0.30)	465.94 (63.92)	46.09 (8.05)
RD Group (*n* = 18)	1.89 (0.37)	472.45 (69.27)	57.74 (19.28)

Figure 2. Group Differences for Fixation Count (A.); Fixation Duration (Milliseconds; B); and Saccade Duration (Milliseconds; C).

Note. **p* ≤ .05, ** *p* ≤ .001; 95% Confidence Interval Error Bars.

5.5 Discussion

The current study examined eye movement patterns during rapid naming in young children to better elucidate the extent to which the temporal constraints in eye movements and attention shifting predict and can therefore be considered reflective of RAN performance. We are assuming that if eye movements during RAN explain significant variance in RAN performance, this should establish that eye movements can be used to operationalize and temporally sequence the microcosm of attentional and higher cognitive processes required for successful object recognition and verbalization as in RAN. Such knowledge also facilitates understanding of the relationship between RAN and oral text reading. The results provide evidence in support of the notion that RAN and text reading ability (accuracy, rate and comprehension) can be significantly predicted by the efficiency of eye movement behaviour during RAN in 5-8-year-old children and that these eye movements also successfully differentiate age-matched children with and without reading difficulties. Moreover, our findings indicate that the average fixation duration and fixation count per RAN item named is highly predictive of RAN, and that these eye movements and RAN show a strong overlap in their predictive contributions to text reading, suggesting that eye movements recorded during RAN reflect much of the cognitive processing required by both RAN and reading. Our interpretation of these measures are based on research (Eckstein et al., 2017; Kim et al., 2019) demonstrating that individual differences in temporally-based fixation durations are indicative of duration of attentional engagement related to speed of visual, symbolic, and orthographic processing. By comparison average fixation counts per stimuli provide a measure of the spatial distribution of attention indicative of the amount of visual information processed in each fixation.

5.5.1 What Predicts Rapid Naming?

Duration and count of fixations (FD and FC) were recorded during RAN and were found to contribute significantly to RAN performance (92.3%), raising the question of variable independence. Eye movement variables have been interpreted as highly reflective of overall RAN performance rather than as independent, individual predictors. Since our results indicated that eye movements did not entirely account for RAN performance, additional factors must contribute to RAN performance. Our results are consistent with those reported by Al Dahhan et al. (2016a), who found that fixation duration, saccade count and number of regressions accounted for 83% of the variance in rapid naming. Indeed our findings also reiterate meta-analytical evidence (Swanson, Trainin, Necoechea, & Hammill, 2003) showing that while phonological awareness and RAN correlate, they load to separate factors of reading indicative of an inadequate explanation for rapid naming ability and suggestive that fixation duration times are not solely mediated by the time needed for phonological activation and retrieval at each fixation. Other evidence against a phonological interpretation comes from Compton (2003) who showed that increasing the visual (orthographic) similarity of the letters within a RAN task negatively affected performance to a much greater extent than increasing phonological similarity. Furthermore, Georgiou, Parrila, Cui, and Papadopoulos (2013) showed that while rapid discrete naming of stimuli (presented one-at-a-time) has similar phonological processing requirements to rapid serial naming of multiple stimuli (presented in an array), it is less well correlated to reading. The relationship between RAN and reading also increased considerably when the ‘naming’ aspect of RAN was accounted for by controlling the effect of discrete RAN on serial RAN performance, suggesting that speed of lexical access does not significantly mediate the RAN-reading relationship (Logan, Schatschneider, &

Wagner, 2011). Consistent with this research, our findings show that eye movement patterns, specifically the amount of time needed to acquire information (FD) and how much information is processed at each fixation (FC), are the most important factors in predicting RAN performance, suggesting that it is not phonological skills that are important for RAN ability, but rather the broader cognitive and attentional process (i.e., the 'microcosm') that eye movements incorporate.

5.5.2 What Predicts Text Reading Skills?

Duration and count of fixations (FD and FC) each made significant contributions to reading accuracy, comprehension, and rate in young readers – together accounting for 36.3%, 31.6%, and 36.2% of the variance respectively. This is higher than the findings of Al Dahhan et al. (2016a), who found that eye movements during RAN only accounted for 15% of the variance in word reading skill. We argue that the larger predictive power of RAN-based eye movements in the current study is likely to reflect the use of a text reading measure, rather than word lists, as gaze patterns during RAN would be a closer approximation of the eye movements required in oral text reading.

Entering the eye movement components into the text reading regressions before RAN, enabled investigation of the unique contributions of eye movements to reading as well as further assessment of the RAN-reading relationship. As expected, once FD and FC had been accounted for, RAN only contributed a further 5.2% of variance to reading accuracy, 4.9% to comprehension and no further significant variance to reading rate. This highlights not only an important overlap of contribution between RAN and the fixation variables to text reading ability, but also a small but important contribution of RAN to text reading independent of the variance explained by eye movements. When all predictors were compared once RAN was added to the regression analyses, FD and FC were unsurprisingly no longer significant unique predictors for reading accuracy, comprehension or rate, with RAN becoming the strongest predictor. Thus, the amount of time needed to acquire information (FD) and the number of fixations needed to acquire this information (FC) is closely related to individual differences in reading performance, suggesting that proficiency in fixation behaviour can play a role in elucidating much of the relationship between RAN and reading.

5.5.3 Do Eye Movements Differentiate Children with and without Reading Difficulties?

Children with reading difficulties were shown to have less proficient fixation characteristics than chronological-age matched controls, with proficiency being measured as average length of fixation duration and number of fixations (1.89 vs 1.55 fixations) needed for successful naming of each RAN stimuli. Interestingly, neither of these groups showed eye movement differences when compared to a younger control group (1.73 fixations) who were matched on reading-age to those with reading difficulties. No difference in saccade duration was found between groups. The results are comparable with other eye tracking studies of RAN (Al Dahhan et al., 2016a; Yan et al., 2013). Children with reading difficulties (aged 9-10 years) have been shown to perform significantly worse than age-matched controls for RAN task efficiency errors, fixation durations, regressive fixations, articulation times, and pause times (Al Dahhan et al., 2016a). Similarly, Yan et al. (2013) reported that 10 year-old Chinese children with reading difficulties process less parafoveal information, requiring more attention for local (foveal) processing of individual letters than controls, inevitably inhibiting their ability to anticipate the next character/icon and hence the rate of rapid naming. This would also result in requiring more fixations per stimuli. It appears that those with reading difficulties are generally less efficient than aged-matched normal readers in their eye movement driven temporal processing of information on RAN tasks, despite being familiar with the stimuli; and therefore, apparently requiring more attention and longer fixations for the required cognitive processes.

The less mature eye movement patterns seen in those with reading difficulties may also result from spatial and temporal sequencing deficits associated with impaired magnocellular processing and neural timing (Stein, 2003). It has been suggested that deficient magnocellular neurons are likely to reduce attentional focus, preventing the linked parvocellular neurons from isolating and sequentially processing the relevant information, and resulting in the diffused attentional distribution experienced by those with a reading disorder (Facoetti, Paganoni, & Lorusso, 2000; Geiger, Lettvin, & Fanhle, 1994; Lawton, 2007; Laycock, Crewther, & Crewther, 2012; Laycock & Crewther, 2008; Lorusso et al., 2004). This would lead to reduced efficiency in cognitively extracting information during fixations, leading to more fixations, longer fixations and more regressions (Stein, 2003), and highlights the increasing importance of investigating eye movement patterns in both reading research and clinical settings.

5.5.4 Limitations and Future Directions

The statistical limitation of using a continuous variable (Reading Accuracy on the Neale) to determine group membership in the sub-sample comparison analyses is an important one, but was performed with the sound rationale of comparing clinical and neurotypical populations to further inform understanding of reading difficulties (Cohen, 1988). It is also acknowledged that the use of a fixation count variable partially based on RAN performance (average number of fixations per stimuli named) may pose a statistical limitation influencing the results of the RAN regression. This is of particular importance for samples of more proficient readers who may make a single fixation per stimuli, as this would lead to fixation count becoming the inverse of the number of RAN stimuli named. However, the current study of emerging readers included children with reading difficulties through to fluent readers, and as such there was range of variability in fixation count (i.e., 1.13-2.52 fixations per stimuli; see Table 1) within the sample. It will be important for future research to carefully consider the influence of interdependency of eye movements variables with measures of the task in which they are recorded. What also remains to be further investigated is the influence of the underlying cognitive processes on eye movement patterns and how these processes link to individual eye movement variables during RAN. For instance, there is already some evidence to suggest that the average duration of fixation may reflect efficiency of visual/orthographic acquisition from the target stimulus (Al-Wabil & Al-Sheaha, 2010; Al Dahhan et al., 2016b; Bellocchi, Muneaux, Bastien-Toniazzo, & Ducrot, 2013). RAN itself also clearly involves well-directed visuo-attention and processing, as well as speed of orthographic, phonological and semantic identification, and ability to inhibit previously named stimuli, sequentially update, and monitor ensuing information (Executive function; see Al Dahhan et al., 2016b; O'Brien et al., 2012). Deficits have been found in those with reading difficulties in each of these aforementioned areas (Menghini et al., 2010; Ramus et al., 2003; Reid, Szczerbinski, Iskierka-Kasperek, & Hansen, 2007). Finally, while the current study does not address the mechanistic link of eye movements and reading, there are already a number of reading intervention studies that target eye movements (see reviews by Bucci, 2019; Peters, De Losa, Bavin, & Crewther, 2019).

5.6 Conclusion

In summary, the findings of the current study add to the body of evidence supporting the notion that eye movements can be used as surrogate measures to investigate many of the cognitive and attentional processes that underpin the relationship between RAN and reading. While those advocating that RAN and the RAN-reading relationship are predominantly reflective of phonological processes continue to be cited (Clarke et al., 2005; Savage et al., 2007; Torgesen et al., 1997; Vukovic & Siegel, 2006; Wagner, Torgesen, & Rashotte, 1994; Ziegler et al., 2010), our results add to the literature supporting an alternative explanation (Al Dahhan et al., 2014; Compton, 2003; Jones et al., 2008; Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007; Thomson, Crewther, & Crewther, 2006). Rather, RAN and reading are more likely related by the ability to rapidly process multiple visual stimuli via a cognitive 'microcosm', as originally proposed by Denckla (1988). As such behaviour can be measured by fixation behaviour during RAN, eye movement patterns demonstrated during RAN should provide a way to further elucidate the RAN-reading relationship. Further research into how eye movement measurements can provide real-time insight into the cognitive processes underlying RAN and reading, including mapping cognitive processes to specific eye movements, is the next step in understanding the association between RAN and reading.

5.7 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

5.8 Author Contributions

JP, EB and SC contributed to the conception and design of the study; JP collected the data, performed the statistical analysis and wrote the first draft of the manuscript; all authors contributed to manuscript revision, and read and approved the submitted version.

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CHAPTER 6

Action Video Game Training Improves Text Reading Accuracy, Rate and Comprehension in Children with Dyslexia: A Randomized Controlled Trial

6.1 Abstract

Dynamic visual attention training using Action Video Games (AVGs) is a promising intervention for children with dyslexia. This study investigated the efficacy of five hours (10x30 min) of AVG training in dyslexic children (aged 8-13) using 'Fruit Ninja', while exploring whether increasing attentional and eye movement demands enhanced AVG effectiveness. Regular (AVG-R; *n* = 22) and enhanced AVG training (AVG+; *n* = 23) were compared to a treatment-as-usual comparison group (*n* = 19) on reading, rapid naming, eye movements and visuo-temporal processing. Playing 'Fruit Ninja' for only five hours significantly improved reading accuracy, rate, comprehension and rapid naming of both AVG groups, compared to the comparison group, though increasing attentional demands did not enhance AVG efficacy. Participants whose low contrast magnocellular-temporal processing improved most following AVG training also showed significantly greater improvement in reading accuracy. The findings demonstrate a clear role for visual attention in reading and highlight the clinical applicability of AVGs as fun, engaging interventions for dyslexia that could be easily implemented in schools.

6.2 Introduction

Dynamic visual attention training using Action Video Games (AVGs) produces significantly greater reading rate and fluency improvements in children with developmental dyslexia compared to non-AVG control interventions, with moderate-to-large effect sizes (see systematic review by Peters, De Losa, Bavin, & Crewther, 2019). As AVGs do not involve any direct teaching of phonological, orthographic or reading skills, it is the attentional demands of playing AVGs that have been associated with these reading improvements (Franceschini et al., 2013). AVGs have also been shown to benefit rapid automatic naming (Luniewska et al., 2018), visual attention and phonological skills (Franceschini et al., 2013; Franceschini et al., 2017). As such, AVG attention training may be more appealing for children with dyslexia and provide a more wide-spread benefit to reading subskills (Bediou et al., 2018; Durkin, 2010) as compared to current treatment options such as phonics training, which is efficacious in remediating single word identification skills (i.e., irregular word accuracy and sight words; McArthur et al., 2018). However, further work is needed to determine which elements of dynamic visual attention contribute most to developing such skills, and to expand upon past findings by using different AVGs and training durations. These findings will help to inform planning for fast clinical and educational application.

6.2.1 Attentional Impairments in Dyslexia

Reading is a dynamic process reliant on temporally and spatially accurate attention, with well-organized eye movements to shift attention. Those with dyslexia often demonstrate impairments in dynamic visual attention skills, including temporal processing (Brown, Peters, Parsons, Crewther, & Crewther, 2020), distribution of attention (Facoetti, Paganoni, & Lorusso, 2000), 'sluggish attentional shifting' (Franceschini et al., 2018), and inefficient planning and coordination of rapid sequential eye movements during reading and non-reading tasks (Caldani, Gerard, Peyre, & Bucci, 2020a; Henry, Van Dyke, & Kuperman, 2018; Peters, Bavin, & Crewther, 2020b). Such dynamic attention is predominantly driven by the magnocellular-dorsal visual stream that is responsive to high temporal and low spatial frequencies, and frequently found to be impaired in dyslexia (Stein, 2019; Stein & Walsh, 1997).

6.2.2 The Neuroscience of AVGs

AVGs are characterized by their fast pace, high sensory-motor and cognitive load (Green & Bavelier, 2003), and requirement for frequent, rapid motor responses to the presentation of multiple spatio-temporally unpredictable and fast-moving stimuli to ensure rapid switching between focused and distributed attentional states (Bediou et al., 2018; Green & Bavelier, 2003, 2012). Thus, AVGs require many of the same visual attention skills impaired in dyslexia. Experienced AVG players reliably demonstrate faster magnocellular-temporal processing (Li, Polat, Makous, & Bavelier, 2006), less activation in motion-sensitive regions (MT/MST) when viewing moving distractors, and less recruitment of the fronto-parietal attention network in response to increased attentional demands (Bavelier, Achtman, Mani, & Föcker, 2012). This suggests that AVG players more easily manage increased attentional demands and are better at suppressing distracting irrelevant information (Bavelier et al., 2012). As such, AVG training for dyslexia may primarily act to improve magnocellular-dorsal stream efficiency (Franceschini et al., 2013) and indirectly improve reading skills. However, to date, studies linking magnocellular and reading improvements following AVG training in dyslexia are limited (Gori, Seitz, Ronconi, Franceschini, & Facoetti, 2016).

6.2.3 AVG Training in Dyslexic Children

Systematic review of the literature indicates that AVGs are a promising treatment for dyslexia (Peters et al., 2019). The review found that AVGs are efficacious in improving reading fluency and rate, but the few studies that had examined reading accuracy or comprehension outcomes reported no improvement, suggesting more research into these reading subskills is required (Peters et al., 2019). Furthermore, investigations are needed to identify the elements of dynamic attention that contribute most to the efficacy of AVG training, since AVGs may not all be equivalent. One option is to investigate whether efficacy could simply be enhanced by increasing the attentional demands via further reliance on eye movements that shift and direct attention (Kühn et al., 2014). However, playing action games via eye tracking requires conscious motor direction of eye movements to make the appropriate motor actions needed to play, i.e., placing much greater demand on attentional flexibility and planning. While AVG studies to date have not assessed eye movement outcomes, other dynamic attention training programs have been shown to improve attention, reading and eye movements (Caldani, Gerard, Peyre, & Bucci, 2020b; Facoetti, Lorusso, Paganoni, Umiltà, & Mascetti, 2003) and so studies using AVGs are needed to build on these past findings.

Of the nine existing published studies most have used ‘Rayman Raving Rabbids’ with 12 hours of training over two weeks (Bertoni, Franceschini, Ronconi, Gori, & Facoetti, 2019; Blaesius & Fleck, 2015; Franceschini & Bertoni, 2019; Peters et al., 2019). Yet, even a single AVG session can reduce reading errors immediately afterwards (Blaesius & Fleck, 2015), suggesting that shorter training may also be successful. Therefore, studies using different AVGs and shorter training times than used previously are important to extend the research base and determine optimal training length.

6.2.4 The Present Study

The present study aimed to investigate whether AVG training, and in particular, AVG training with increased demands on dynamic visual attention via eye movements, would result in greater improvements as compared with a comparison group receiving only treatment-as-usual school-based reading intervention. Text reading accuracy, rate and comprehension, eye movement behaviour during rapid naming, and magnocellular tasks of temporal efficiency were included as outcome measures. 'Fruit Ninja' (Halfbrick, 2010), a simple and non-violent fruit-slicing game which meets AVG criteria, was selected for use in both AVG training groups; it has not previously been investigated. A training duration of 5 hours (ten, 30-minute sessions over a 2-week period) was used to determine if a shorter duration than used in most previous studies would also lead to improvement in reading. Those in the AVG training group with increased attentional demands (AVG+) played Fruit Ninja using eye tracking to control the cursor on the screen, while those in the regular AVG training group (AVG-R) played using a standard computer mouse, comparable to the motor controllers used for most video game consoles.

It was hypothesized that:

1) Dynamic attentional training, using AVGs, would lead to significantly greater improvement in reading rate and rapid naming than the treatment-as-usual comparison group. The benefit to reading accuracy, comprehension, eye movements and magnocellular measures were also explored.
2) AVG+ training, with increased attention demands via eye movements, would be more effective than regular AVG training (i.e., AVG-R).

6.3 Method

6.3.1 Participants

A total of 64 dyslexic children aged 8;09 to 13;01 years (Grades 3-6) were recruited from Melbourne metropolitan primary schools to participate in the study. In order to be included in the study, participants required (1) a history of reading difficulties as reported by teachers or parents and/or a formal diagnosis of dyslexia, and (2) reading performance at least 1 SD (O'Brien, Wolf, & Levett, 2012) below age-standardized norms in one or more area of reading (text reading accuracy, rate and/or comprehension) on the York Assessment of Reading for Comprehension - Primary Reading (YARC; Snowling et al., 2012). Diagnoses were confirmed by a psychologist on the research team. Participants were also required to have normal intelligence (Standard score ≥85 for age on the Raven's Matrices test), normal or corrected-to-normal vision and hearing, and English as their primary language. Children with known medical and neurodevelopmental disorders other than dyslexia were excluded. Parents of participants provided written informed consent for their child to engage in the study and all children who participated provided verbal assent. The participants were blind to the aims of the study. The study was registered as a clinical trial with the Australian New Zealand Clinical Trails Registry (registration number ACTRN12618001709235; registration dated 16/10/2018) and performed in accordance with the World Medical Association Declaration of Helsinki and with ethics approval granted by the La Trobe University Faculty Human Ethics Committee and the Victorian State Department of Education.

Table 1. *Baseline Comparisons for Age and Non-Verbal Intelligence for Intervention and Comparison Groups*

	AVG+ Group n = 23	AVG-R Group n = 22	Comparison Group n = 19			
	M (SD)	*M (SD)*	*M (SD)*	F (2, 61)	p	η^2
Age	10.37 (0.95)	10.49 (1.05)	10.73 (0.96)	0.695	.503	.02
Nonverbal Intelligence	101.96 (8.75)	103.27 (9.09)	105.26 (7.68)	0.777	.464	.02

Participants at each school were randomly allocated using a random number generator to either AVG+ training (n = 23), AVG-R training (n =22), or a 'treatment-as-usual' comparison group (n = 19). The comparison group were not provided with training by the researchers but continued to receive school-based reading remediation based on various phonics-based programs. As did all AVG players. As shown in Table 1, groups did not significantly differ in chronological age or nonverbal intelligence. Groups also did not differ on reading accuracy (p = .160), reading rate (p = .893), reading comprehension (p = .444), or rapid number naming performance (p = .583) at baseline (T1; see Table 2 for descriptives), and were an average of 2.15 years behind age expectations in reading accuracy, 1.98 years behind in reading rate, and 0.97 years behind in reading comprehension.

6.3.2 AVG Training Procedure

Children in each of the AVG groups completed dynamic attention training using AVGs in small groups of 3-4 in a quiet room at their school. The ten, 30-minute sessions occurred each weekday for two weeks, for a total of 5 hours. Both AVG training groups played Fruit Ninja via the android emulator, BlueStacks App Player (BlueStacks, 2018), on a 23 inch Dell computer screen to minimise any differences between training methods (e.g., screen size) as the eye tracking program required a Windows operating system.

'Fruit Ninja' meets AVG criteria as it requires players to quickly slice fruit that moves rapidly with temporal and spatial unpredictability from the periphery of the screen, with points awarded for each fruit sliced. Players must also switch between following a target and monitoring the entire scene as well as planning and inhibiting responses so that non-targets (i.e., 'bombs') are avoided, and must rapidly make decisions about how best to respond to the visual scene to achieve the most points.

The main aim of 'Fruit Ninja' is to slice as many fruits as possible. Players must make a single swipe motion through each fruit to earn a point, with extra points awarded for slicing multiple fruits with one swipe (called combos) or slicing 'special' fruit. Children in both AVG training groups were allowed to freely play any of the Fruit Ninja mini-games during their training sessions. Scores in each mini-game earn game currency and increase the players experience points, helping players progress to the next level and gain access to new features. Players then use game currency to buy items that provide additional powers for use during the games. Children could also complete various missions (e.g., slice 8 green apples in one game) to earn additional game currency.

6.3.2.1 AVG-R training. Children in the AVG-R group played Fruit Ninja using a computer mouse to control the cursor on the screen. They were required to move the mouse in a slicing motion while holding down the left button in order to slice fruit.

6.3.2.1 AVG+ training. Children in the AVG+ group played Fruit Ninja by using their eye movements to control the cursor on the screen. This was theorised to place an increased demand on dynamic visual attention through accurate and well-timed eye movements. During training sessions, participants had their eye movements tracked binocularly using a Gazepoint GP3HD screen mounted infrared camera with 150 Hz sampling rate (Gazepoint). The Gazepoint Fruit Ninja application programming interface was also used to translate eye movements into cursor movement during AVG play. Before each training session, participants would undergo a 9-point calibration procedure. Participants were provided with a chin and forehead rest to reduce movement for initial training sessions, and as needed for later training sessions (i.e., if head movement resulted in eye tracker drop out), though almost all children in the AVG+ group adapted sufficiently and quickly in keeping their head still while just moving their eyes.

6.3.2 Materials

All participants completed cognitive and reading assessment 3 to 5 days before (Baseline; T1) and after (T2) the training period (i.e., a total of 20-24 days apart) with tasks administered in randomized order. Assessments occurred individually in a quiet room at the child's school. Participants completed all computerised and psychophysical tasks, including AVG training, at a viewing distance of about 59cm.

6.3.2.1 Nonverbal intelligence. Nonverbal intelligence was assessed at baseline using the Ravens Coloured Progressive Matrices for participants aged 5-11 years (Raven, Court, & Raven, 1998) or the Ravens Standard Progressive Matrices for participants aged 12+ years (*Standard Progressive Matrices: Australian Manual*, 1958). Each test contains a series of matrices of increasing complexity. Age-based standard scores were calculated using normative data.

6.3.2.2 Text reading. The YARC was used to assess text reading accuracy, rate and comprehension skills (Snowling et al., 2012) . The task requires children to successfully read two passages of text aloud, while being timed, and answer questions about each text to assess both literal and inferential text comprehension. The two passages to be read are selected from a series of seven passages of increasing difficulty, corresponding to each grade level of primary school. Passage selection is based on each child's grade level and reading proficiency in accordance with the YARC manual. Equivalent passage levels from alternative forms (A and B) were used for T1 and T2, in a counterbalanced order. Age-based standardized scores and age equivalence estimates for reading accuracy, rate and comprehension performances were used. FastaReada (Elhassan, Crewther, Bavin, & Crewther, 2015), a psychophysical measure of reading fluency, was also included in data collection, but majority of participants were not able to reliably pass the practice trial, and so the task has been excluded from data analysis.

6.3.2.3 Rapid automatic naming. The number rapid naming task from the CTOPP-2 was assessed at both T1 and T2. The task, a strong predictor of reading, measures rate of visual to verbal information processing. It was also used to study changes in eye movement behaviour as it minimizes stimulus-based factors known to influence eye movements, including word difficulty, length and predictability (Peters et al., 2020b). Participants were required to rapidly name aloud 36 stimuli (four lines of nine stimuli). Time taken to name all stimuli was recorded and standardized scores are reported. The letter RAN task from the CTOPP-2 was also completed by participants, but as results between the number and letter versions (including eye movements) were comparable, this task has not been included further for brevity.

6.3.2.4 Eye movements during rapid automatic naming. Eye movements were recorded binocularly during the rapid naming task using a Gazepoint GP3HD screen mounted infrared camera with 150 Hz sampling rate (Gazepoint). The GP3HD tracks vertical and horizontal eye positions with an average gaze position accuracy of 0.5 degrees. Participants had their head placed in a chin and forehead rest to reduce movement. Before beginning the task, each participant underwent a 9-point eye movement calibration procedure. The variables, fixation duration, fixation count, and regression count were extracted for statistical analysis. Fixation duration was calculated as the average (mean) temporal length of fixations, fixation count was defined at the total number of fixations made, and regression count was defined as the number of backward saccades made across previously named stimuli.

6.3.2.5 Magnocellular temporal processing tasks. As it is theorized that AVGs improve reading via the magnocellular system, two achromatic flicker fusion tasks modulated at high (75%) and low (5%) luminous contrast were included as surrogate measures of the temporal processing thresholds of the magnocellular pathway previously. The tasks were previously used by Brown, Corner, Crewther, and Crewther (2018), and were assessed at T1 and T2. Four LEDs conveyed light into separate 6 mm diameter optic fibre light guides which were presented flush in a free-standing wooden panel in a diamond-array subtending 1.0◦, center-to-center, at the eye. Each task consisted of a four-alternative forced-choice design with 32 trials and used a Parameter Estimation by Sequential Testing (PEST) procedure (For further details about task design, see Brown et al., 2018). Participants were instructed that one LED light per trial (demarcated by a high-pitched beep) would flicker for 3 seconds and at the end of the trial (indicated by a low-pitched beep) they were required to indicate which light source they saw flicker or guess when they were unsure. The order of high and low contrast conditions was counterbalanced to control for practice effects, and participants were provided with a familiarization practice session. Participants completed the tasks in a dimly lit room. The start of each trial was manually controlled by the experimenter to ensure participants were looking at the display, ready for the trial to commence.

6.4 Data Analysis

An *a priori* power analysis indicated that there was 95% power to detect a large effect size at p =.05 with 18 participants per group. As adjustment or removal of outliers represents a potential source of bias in intervention trials, handling of outliers was conducted in accordance with the Statistical Principles for Clinical Trials Guidelines (1998). Several outliers just outside the normal distribution were identified, but not found to influence results, so were retained (i.e., no observations were excluded). Standard scores, rather than raw scores, for clinical tasks were used to analyse performance change between T1 and T2 as they capture meaningful changes in performance as based on age-normative data. For normally distributed variables, the Standard Mean Difference (SMD; Hedges g), an effect size measure comparing the changes (T2-T1) between two groups, was calculated for each outcome variable to compare the efficacy of each AVG group to the comparison group, and compare the efficacy of the AVG+ and AVG-R groups to each other. The magnitude of SMD is interpreted as small = 0.2, moderate = 0.5 and large = 0.8. Positive SMDs are in favour of the first group listed within the comparison. Normality was confirmed via assessment of skewness and kurtosis, Kolmogorov-Smirnov values, and visual inspection of histograms and box plots.

To determine whether the AVG groups improved significantly more than the comparison group, two-way mixed design (time [T1 and T2] by group [AVG+, AVG-

R, comparison group]) analysis of variances (ANOVAs) were conducted for each outcome. Pairwise comparisons of outcomes between groups at T1 and T2 were then used to determine whether the AVG+ group showed greater improvement to the AVG-R group. Means and confidence intervals for each outcome variable, group and time point is shown in Table 3. Correlation and regression analyses were then used to explore the relationship between flicker fusion performances and improvements in reading outcomes following AVG training.

To assist with interpretation of results in clinically meaningful terms, normative age equivalent estimates from the clinical test manuals (i.e., YARC, CTOPP-2) were used to provide an estimate of average months of improvement.

6.5 Results

6.5.1 Reading Improvements

As shown in Table 2, Two-Way Mixed Design ANOVA revealed a significant interaction effect between time and intervention for reading accuracy. Simple effects analysis showed significant differences between groups post-intervention (T2), but not at baseline (T1). Simple effects analysis followed by pairwise comparisons indicated that reading accuracy significantly improved only in the AVG groups between T1 and T2, with a comparable level of improvement in the AVG+ and AVG-R groups, p =.418 (Figure 1). The average improvement in reading accuracy, as based on normative age equivalent estimates from the YARC, was: AVG+ = 6.31 months, AVG-R = 8.55 months, and comparison group = 1.26 months. Descriptives and SMDs are shown in Table 3.

A similar pattern of results was observed for reading rate and reading comprehension, which also showed a significant time and intervention interaction effect. For both measures, the three groups did not differ in performance at T1.

Again, the AVG groups, but not the comparison group, had improved significantly at T2, with the improvement in both reading rate and reading comprehension comparable between the AVG+ and AVG-R groups (p =.754 and p =.999, respectively). The average improvement in reading rate was equivalent to: AVG+ group = 6.31 month, AVG-R group = 10.33 months, and comparison group = -0.69 months. The average improvement in reading comprehension was equivalent to: AVG+ = 17.82 months, AVG-R = 19.90 months, and comparison group = -1.48 months.

Table 2. *Analysis of Variance Results and Summary of Post Hoc Analyses for the Effects of Intervention on Measures of Reading, Eye Movements and Magnocellular Tasks*

	Time x Intervention	Simple Effects for Time	Simple Effects for Intervention	
Reading Accuracy	Sig. Wilk's $\lambda = .83$, $F(2, 60) = 6.00$, $p = .004$, $\eta_p^2 = 0.17$	• Comparison (T1 = T2) • AVG+ (T1 < T2) • AVG-R (T1 < T2)	T1: $p = .160$, $\eta_p^2 = 0.06$ T2: $p = .001$, $\eta_p^2 = 0.21$	T1: Comparison = AVG+ = AVG-R T2: Comparison ≠ AVG+ or AVG-R; AVG+ = AVG-R
Reading Rate	Sig. Wilk's $\lambda = .74$, $F(2, 60)= 10.79$, $p <.001$, $\eta_p^2 = 0.27$	• Comparison (T1 = T2) • AVG+ (T1 < T2) • AVG-R (T1 < T2)	T1: $p = .893$, $\eta_p^2 = 0.04$ T2: $p = .048$, $\eta_p^2 = 0.09$	T1: Comparison = AVG+ = AVG-R T2: Comparison ≠ AVG+ or AVG-R; AVG+ = AVG-R
Reading Comprehension	Sig. Wilk's $\lambda = .79$, $F(2, 60) = 7.91$, $p =.001$, $\eta_p^2 = 0.21$	• Comparison (T1 = T2) • AVG+ (T1 < T2) • AVG-R (T1 < T2)	T1: $p = .444$, $\eta_p^2 = 0.03$ T2: $p < .001$, $\eta_p^2 = 0.25$	T1: Comparison = AVG+ = AVG-R T2: Comparison ≠ AVG+ or AVG-R; AVG+ = AVG-R
Rapid Naming	Sig. Wilk's $\lambda = .81$, $F(2, 60) = 6.95$, $p =.002$, $\eta_p^2 = 0.19$	• Comparison (T1 = T2) • AVG+ (T1 < T2) • AVG-R (T1 < T2)	T1: $p = .622$, $\eta_p^2 = 0.02$ T2: $p = .035$, $\eta_p^2 = 0.11$	T1: Comparison = AVG+ = AVG-R T2: Comparison ≠ AVG+ or AVG-R; AVG+ = AVG-R
Fixation Duration	NS Wilk's $\lambda = .99$, $F(2, 60) = 0.03$, $p =.971$, $\eta_p^2 = 0.01$	• Comparison (T1 = T2) • AVG+ (T1 = T2) • AVG-R (T1 = T2)	T1: $p = .668$, $\eta_p^2 = 0.01$ T2: $p = .727$, $\eta_p^2 = 0.01$	T1: Comparison = AVG+ = AVG-R T2: Comparison = AVG+ = AVG-R
Fixation Count	NS Wilk's $\lambda = .98$, $F(2, 60) = 0.45$, $p =.641$, $\eta_p^2 = 0.02$	• Comparison (T1 = T2) • AVG+ (T1 > T2) • AVG-R (T1 > T2)	T1: $p = .816$, $\eta_p^2 = 0.01$ T2: $p = .184$, $\eta_p^2 = 0.06$	T1: Comparison = AVG+ = AVG-R T2: Comparison = AVG+ = AVG-R
Regression Count	NS Wilk's $\lambda = .97$, $F(2, 60) = 0.81$, $p =.449$, $\eta_p^2 = 0.03$	• Comparison (T1 = T2) • AVG+ (T1 = T2) • AVG-R (T1 > T2)	T1: $p = .539$, $\eta_p^2 = 0.02$ T2: $p = .092$, $\eta_p^2 = 0.08$	T1: Comparison = AVG+ = AVG-R T2: Comparison = AVG+ = AVG-R
Flicker Fusion 5%	NS Wilk's $\lambda = .99$, $F(2, 60) = .14$, $p =.872$, $\eta_p^2 = .01$	• Comparison (T1 = T2) • AVG+ (T1 = T2) • AVG-R (T1 = T2)	T1: $p = .748$, $\eta_p^2 = 0.01$ T2: $p = .686$, $\eta_p^2 = 0.01$	T1: Comparison = AVG+ = AVG-R T2: Comparison = AVG+ = AVG-R
Flicker Fusion 75%	NS Wilk's $\lambda = .92$, $F(2, 60) = 2.78$, $p =.070$, $\eta_p^2 = .09$	• Comparison (T1 = T2) • AVG+ (T1 < T2) • AVG-R (T1 = T2)	T1: $p = .251$, $\eta_p^2 = 0.05$ T2: $p = .564$, $\eta_p^2 = 0.02$	T1: Comparison = AVG+ = AVG-R T2: Comparison = AVG+ = AVG-R

Note. Sig = significant; NS = Non-significant; AVG-R = Action Video Game-Regular Group; AVG+ = Increased Attention Action Video Game Group; Comparison = Comparison Group.

Table 3. *Averages, 95% Confidence Intervals and Standard Mean Differences of Outcome Measures for Each Group and Timepoint.*

	AVG+ Group *n* = 23		AVG-R Group *n* = 22		Comparison Group *n* = 19		Standard Mean Differences (±CI)		
	T1 M (±CI)	T2 M (±CI)	T1 M (±CI)	T2 M (±CI)	T1 M (±CI)	T2 M (±CI)	AVG+ vs Comparison	AVG-R vs Comparison	AVG+ vs AVG-R
Reading Accuracy	81.50 (3.68)	85.91 (4.01)	82.95 (3.39)	89.77 (3.30)	78.21 (2.90)	79.26 (3.60)	0.646 (0.63)	1.110 (0.66)	-0.463 (0.60)
Reading Rate	81.27 (4.30)	86.32 (3.98)	82.73 (3.83)	89.82 (4.09)	82.37 (5.48)	82.11 (4.87)	1.052 (0.65)	1.457 (0.69)	-0.405 (0.59)
Reading Comprehension	92.86 (6.42)	107.55 (4.82)	90.36 (4.89)	104.86 (5.85)	96.21 (7.42)	90.32 (6.29)	1.125 (0.66)	1.115 (0.66)	0.010 (0.59)
Rapid Naming	88.04 (4.72)	94.13 (5.60)	87.85 (2.99)	93.81 (4.73)	85.26 (4.88)	85.26 (4.65)	1.059 (0.65)	1.038 (0.66)	0.024 (0.59)
Fixation Duration	319.61 (21.88)	330.64 (17.81)	316.04 (21.84)	323.31 (24.04)	330.87 (26.80)	337.22 (29.45)	0.079 (0.62)	0.016 (0.62)	0.064 (0.61)
Fixation Count	57.05 (3.75)	50.95 (2.95)	58.67 (5.79)	52.05 (3.69)	59.21 (4.87)	55.95 (4.84)	0.243 (0.62)	0.287 (0.62)	-0.044 (0.60)
Regression Count	8.81 (1.42)	7.24 (1.04)	10.05 (2.24)	7.33 (1.59)	10.16 (1.83)	9.32 (1.62)	0.159 (0.62)	0.409 (0.63)	-0.249 (0.61)
Flicker Fusion 5%	46.58 (1.87)	47.29 (1.50)	45.77 (2.11)	46.18 (1.65)	46.96 (2.61)	46.85 (2.34)	0.172 (0.61)	0.105 (0.62)	0.059 (0.60)
Flicker Fusion 75%	50.25 (1.62)	52.58 (1.56)	49.89 (1.72)	51.91 (2.39)	52.44 (3.24)	50.99 (2.22)	0.705 (0.63)	0.604 (0.63)	0.101 (0.59)

Note. AVG-R = Action Video Game-Regular Group; AVG+ = Increased Attention Action Video Game Group; ±CI = +/- 95% Confidence Interval; Standard Mean Differences are interpreted as small=0.2, moderate=0.5 and large=0.8, with positive scores in favour of the first group listed in the comparison.

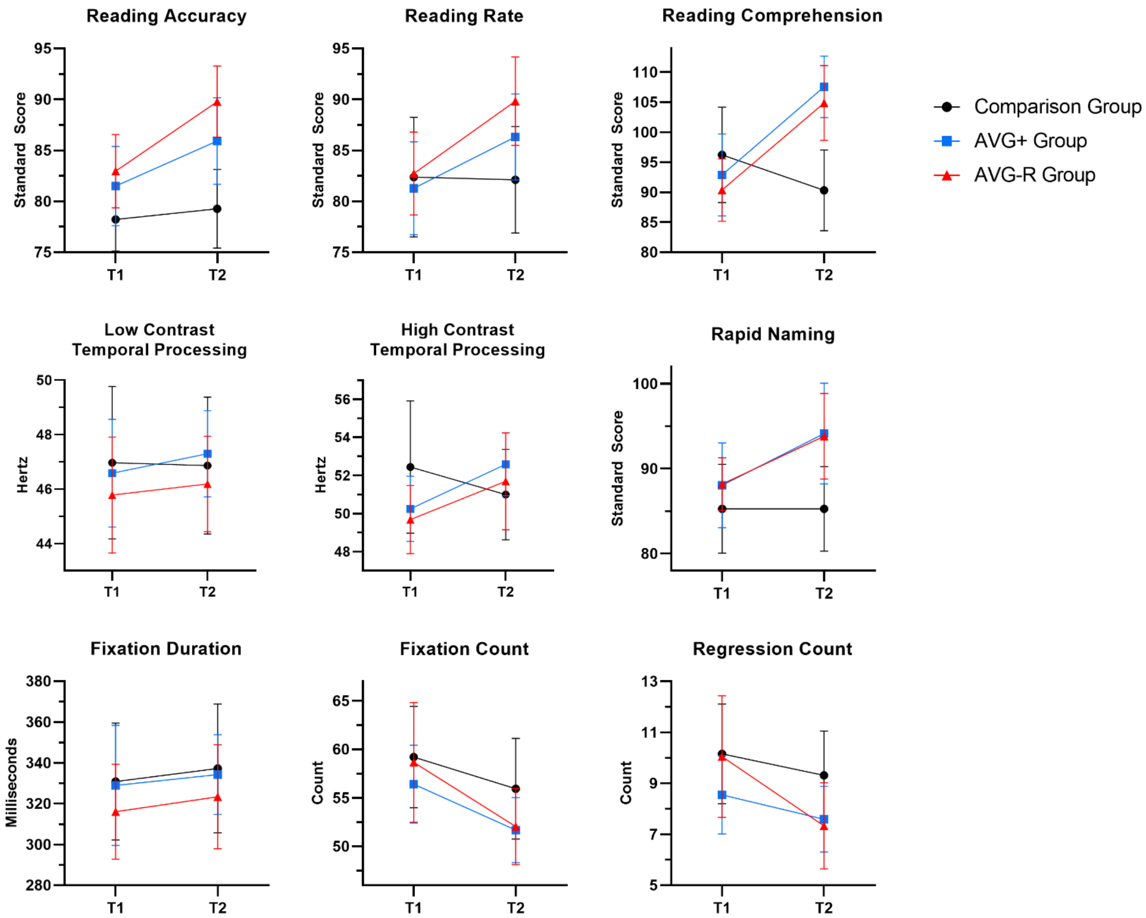

Figure 1. Dyslexic children's performances on reading, rapid naming, eye movements and temporal processing measured before (T1) and after (T2) AVG+ training, AVG-R training or treatment-as-usual (comparison group). Means and 95% confidence intervals are displayed.

6.5.2 Rapid Automatic Naming and Eye Movements

As illustrated in Figure 1, ANOVA showed a signification time and intervention interaction effect for rapid naming (see Table 2 for analysis results and Table 3 for descriptives and SMDs). No group differences were observed at T1, while only the AVG groups showed significantly improved naming speed at T2, with no difference in performance occurring for the comparison group. There was no difference in amount of improvement between the AVG+ and AVG-R groups at T2, p =.999. The average improvement in rapid naming, as based on normative age equivalent estimates from the CTOPP-2, was equivalent to: AVG+ = 10.82 months, AVG-R = 17.28 months, and comparison group = 1.10 months.

No significant effects were observed for fixation durations during rapid naming, as no change in the duration of fixations was observed between groups at either T1 or T2 for this task. For fixation count, the interaction effect between time and intervention, and the main effect of intervention group were not significant. However, the main effect for time was significant, indicating a general reduction in number of fixations between T1 and T2 for rapid naming. Similar results were obtained for regression count, where only a significant main effect for time was observed, again indicating a general reduction in regressive saccades during rapid naming between T1 and T2 (see Figure 1).

6.5.3 Magnocellular Temporal Processing

ANOVAs revealed no significant interaction or main effects for low (5%) or high (75%) contrast flicker fusion tasks, indicating no significant changes in detection thresholds between groups from baseline to post-intervention (Figure 1); however, there were moderate effect sizes for both the AVG+ and AVG-R groups as compared with the comparison group (Table 3). Inspection of the confidence intervals also indicated a high degree of variability if FFT performance at both T1 and T2.

This was investigated further to determine if the improvements in reading outcomes following AVG training were related to flicker fusion task performance at baseline (T1) as well as improvement following training. Improvements in the outcome measures were calculated as post-training score (T2) minus baseline (T1) score, and AVG training participants were analysed as a single group as the preceding analyses confirmed the two AVG programs/groups showed comparable efficacy. Pearson correlational analyses indicated that flicker fusion performance at baseline

(T1) significantly correlated with improvements in temporal processing following training. High contrast flicker fusion scores at baseline was also associated with improvements in reading comprehension, while improved low contrast flicker fusion correlated with reading accuracy improvements (See Table 4).

Table 4. *Correlations between Flicker Fusion Performance and Reading Improvement Scores*

	Baseline 5% FFT (T1)	Baseline 75% FFT (T1)	Reading Accuracy Improvement	Reading Rate Improvement	Reading Comp Improvement	Rapid Naming Improvement	5% FFT Improvement	75% FFT Improvement
Baseline 5% FFT (T1)	-	.432**	-.286	.058	.240	-.130	-.745**	-.018
Baseline 75% FFT (T1)		-	-.131	.101	.368*	-.080	-.345*	-.460**
Reading Accuracy Improvement			-	.251	-.145	.024	.334*	-.018
Reading Rate Improvement				-	.113	-.038	-.179	-.122
Reading Comp Improvement					-	-.219	-.196	-.083
Rapid Naming Improvement						-	.099	-.062
5% FFT Improvement							-	.240
75% FFT Improvement								-

Note. *$p < .05$, ** $p < .01$; According to Cohen's guidelines, $r \geq 0.10$, $r \geq 0.30$, and $r \geq 0.50$, represent small, medium, and large effect sizes, respectively; Improvements scores were calculated as post-training score (T2) minus baseline (T1) score.

Based on the significant correlations shown in Table 4, regression analyses were conducted to assess the contribution of low contrast flicker fusion to improvements in temporal processing and reading accuracy following AVG training. Slower low contrast flicker fusion scores at baseline significantly predicted greater improvement in low contrast flicker fusion performance following AVG training, explaining 55.5% of the variance in the regression model; F (1, 42) = 52.363, standardized beta = -.745, $p < .001$. Improvement in low contrast flicker fusion following AVG training was a significant predictor of reading accuracy improvements following AVG training, explaining 11.2% of the variance in the regression model; F (1, 42) = 5.149, standardized beta = .334, $p = .029$.

6.6 Discussion

Reading fluency and comprehension benefit little from current intervention options (Ehri, Nunes, Stahl, & Willows, 2001; McArthur et al., 2018; Suggate, 2014; Wexler, Vaughn, Edmonds, & Reutebuch, 2008). As such, those with dyslexia often continue experiencing substantial reading difficulties throughout life (Gabrieli, 2009). Thus, the development of alternative interventions is essential. Growing evidence demonstrates that dynamic attentional training using AVGs is an effective intervention for dyslexia, particularly for reading rate and fluency. Our results indicate that AVG training also benefits reading accuracy and comprehension. Findings also show that a novel AVG with shorter training demonstrated efficacy comparable to past research, however, AVG efficacy was not enhanced by increasing the demand on dynamic attention using eye movements. Moreover, those with lower flicker fusion scores before AVG training showed the greatest improvement in temporal processing, and improved low contrast flicker fusion significantly predicted reading accuracy improvements.

6.6.1 AVG Training versus Comparison

Children who received AVG training (i.e., AVG+ or AVG-R) significantly improved in text reading accuracy, rate and comprehension, and rapid naming performance as compared with the comparison group, who did not show improvements. Yet, at T2 all three groups demonstrated fewer fixation and regression counts and unchanged fixation durations during rapid naming, suggesting that the increase in rapid naming score after AVG training is likely mediated by something other than increased efficiency of eye movements. AVG training (AVG+ and AVG-R) using ‘Fruit Ninja’ resulted in at least 6 months of improvement across reading skills and rapid naming, with mostly large effect sizes (SMDs) found. The benefit to reading rate is comparable to studies using ‘Rayman Raving Rabbids’ for 12 hours of training (see Peters et al., 2019). It is not clear whether the similar efficacy of the current results, despite only 5 hours of training, may be driven by differences in the effectiveness of the AVGs used, or whether a plateau of intervention efficacy may start to occur after 5 hours of training. This warrants further research.

The current study is only the second to demonstrate reading accuracy improvements following AVG training (see also Blaesius & Fleck, 2015), with the greatest improvement in reading accuracy found in AVG training participants who also showed the highest gains in low contrast magnocellular-temporal processing following AVG training. As all three groups demonstrated equivalent flicker fusion scores at baseline (T1), and the comparison group did not significantly improve in reading outcomes at T2, these changes must be attributed to the effect of AVG training. While improvements on magnocellular outcome measures have been reported in individuals with dyslexia following other types of dynamic attention training (Gori et al., 2016; Lawton, 2016; Qian & Bi, 2015), the current findings provides novel evidence that the degree of reading accuracy improvements following AVG training are related to gains in the temporal processing rate of the magnocellular stream at low contrast. This is consistent with suggestions that the magnocellular stream is responsible for the early visual analysis and spatial selection required in word recognition (Pammer, Hansen, Holliday, & Cornelissen, 2006). Impairments in these initial steps are theorized to cause a bottleneck that then impacts later cognitive processes needed for word recognition - orthographic-to-phonological mapping for example (Pammer et al., 2006).

This is also the first study to show AVG training benefits text reading comprehension. The benefit is likely to be secondary to improvements in reading accuracy and rate, and therefore requiring less cognitive effort, which could allow readers cognitive and attentional capacity to focus on comprehension. It may also be attributed to improvements in skills that underpin the comprehension process - working memory and executive functioning (i.e., integration and inference; Cain, Oakhill, & Bryant, 2004) - as there is evidence to suggest they also benefit from AVGs (Bediou et al., 2018). Nonetheless, further research is needed to confirm these hypotheses.

Furthermore, given that children with slower flicker fusion scores at low contrast before AVG training showed the greatest improvement in low contrast temporal processing, with improved low contrast flicker fusion then predicting reading accuracy improvements. We conclude that AVG training may be most beneficial for dyslexic children with slower temporal processing, as has recently been identified to specifically characterise a subgroup of dyslexic children (Peters, Bavin, Brown, Crewther, & Crewther, 2020a).

6.6.2 AVG+ versus AVG-R training

In contrast to predictions, AVG+ training with increased dynamic attention demands via eye movements did not significantly mediate training efficacy. Those receiving AVG+ and AVG-R training improved comparably, though for most outcomes, AVG-R training tended to show larger, albeit nonsignificant, gains. Placing a continued and increased demand on attention via eye movements may have inadvertently made game play more effortful and challenging, as evidence suggests that game difficulty should be adjusted commensurate with the players ability to maintain engagement (Lach, 2015). Recently, Franceschini and Bertoni (2019) demonstrated that those who get better at playing AVGs over the course of training demonstrate the most cognitive gains. While game scores were not formally monitored in the current study, those in the AVG+ group scored consistently lower than the AVG-R group throughout training. Therefore, it is possible that the AVG+ version of training required much greater neural resources resulting in a higher level of difficulty for children to play and greater cognitive fatigue. The practical advantage of this finding is that AVG-R training can more easily be implemented in a range of settings without the need for specialist eye tracking equipment or training.

6.7 Conclusion

Dynamic attentional training using the AVG, ‘Fruit Ninja’, for as little as 5 hours can significantly improves reading accuracy, rate, comprehension and rapid naming in dyslexic children, despite not directly training reading. Participants whose low contrast magnocellular-temporal processing improved most following AVG training also showed significantly greater improvement in reading accuracy. The short training duration, however, did not result in significant improvements to eye movements. Increasing attentional demands by increasing reliance on eye movements during game play also did not increase efficacy, rather it may have been cognitively fatiguing. Nonetheless, the current evidence supports the view that dynamic visual attention plays an integral role in dyslexia and reading. The study also highlights the clinical applicability of AVGs as a fun, engaging intervention for reading that can improve aspects of reading that are not generally improved with current phonics treatments. AVG training is less resource-demanding than current options (Franceschini et al., 2013; Gabrieli, 2009) and could easily be implemented as a reading intervention in a variety of settings, including schools. Further research is needed to continue investigation into the dynamic attentional mechanisms that drive AVG efficacy, assess longer-term follow up of outcomes, and directly compare AVG and phonics-based interventions. Future investigations should also consider the role of motivational engagement in the efficacy of AVG games.

6.8 Author Contributions

All authors developed the study concept and design under the supervision of S. G. Crewther and E. L. Bavin. Testing and data collection were performed by J. L Peters. Data analysis and interpretation was performed by J. L. Peters and M. J. Murphy. J. L. Peters drafted the manuscript, and M. J. Murphy, E. L. Bavin, and S. G. Crewther provided critical revisions. All authors approved the final version of the manuscript for submission.

6.9 Open Practices Statement

The study was registered as a clinical trial with the Australian New Zealand Clinical Trails Registry, http://www.anzctr.org.au/Trial/Registration/TrialReview.aspx?id=376081 (registration number ACTRN12618001709235; registration dated 16/10/2018). The data have not been made available on a permanent third-party archive, but requests for the data can be sent via email to the lead author.

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CHAPTER 7

General Discussion

7.1 Summary of Objectives

The overall aim of this thesis was to investigate the contribution that the magnocellular (M) pathway makes to reading as a function of rate of visual information processing thresholds and of visual attention engagement and shifting in children with and without dyslexia. Although dyslexia has been the focus of research for more than a century, no single explanation has been able to provide a comprehensive account of the range of reading difficulties that are experienced (Boder, 1970; Castles & Coltheart, 1993; Stein, 2019; Vellutino, Steger, & Pruzek, 1973; Wolf & Bowers, 1999). Moreover, research has tended to investigate reading by studying skills such as phonological awareness, rapid naming and orthographic knowledge (e.g., Vellutino, Fletcher, Snowling, & Scanlon, 2004). While the importance of these skills to reading cannot be understated, few have considered that reading is also a neurobiologically dynamic process and must rely on the dynamic temporo-spatial visual attention of the magnocellular pathway, including well-organized eye movements to shift attention (Stein, 2019).

Hence, the aim of this thesis was to address several gaps in the literature pertaining to the temporal functioning of the M-system, and its role in the rate of activation and shifting of visual attention, in samples of primary school-aged neurotypical and dyslexic children. An in-depth understanding of M functioning and the role of visual attention in dyslexia has important implications for (a) the assessment and diagnosis of dyslexia and its heterogenous subtypes by improving the ability to identify which underlying deficits contribute to each individual's reading difficulties, (b) the provision of new and efficacious interventions, and (c) will address gaps in knowledge that exist in relation to dyslexia. Several objectives were established to empirically address the principle aims of this thesis from a cognitive neuroscience viewpoint, as summarised below:

1. To identify and synthesize the available research to determine the efficacy of visual attentional interventions as a treatment for dyslexia in order to provide recommendations to guide clinical practice.
2. To examine whether children with dyslexia show an impairment in magnocellular-based thresholds of temporal processing of rapid repetitive stimulation as compared with matched neurotypical children, and whether performance on flicker fusion tasks can be used to differentiate children with dyslexia from neurotypical children.
3. To determine the usefulness of eye movements recorded during rapid naming, as measures of the temporo-spatial placement of visual attention, in predicting both rapid naming and reading performance and differentiating dyslexic and typical readers.
4. To extend the research on visual attention interventions for dyslexia by evaluating whether increasing the attentional demands of an AVG enhances the efficacy of AVG, while concurrently exploring the efficacy of a shorter training duration and different action game.

7.2 Summary of Findings

7.2.1 Visual Attention Training as an Intervention for Dyslexia

In Chapter 2, a systematic review was conducted to evaluate the effectiveness of dynamic computerized visuo-attentional interventions aimed at improving reading for dyslexic and neurotypical children aged 5-15. No previous review on this topic was identified, and so findings provided a novel synthesis of the literature. Eighteen studies met inclusion criteria (620 participants; 91.40% dyslexic) and three types of visuo-attentional interventions were identified. Findings showed that low-level visual perceptual training (*n*=5) benefited reading fluency and comprehension, visually-based reading acceleration programs (*n*=8) improved reading accuracy and rate, and action video games (AVG; *n*=5) increased rate and fluency, and reading improvements following these visual attentional interventions were generally equal to or greater than other strategies. These findings show that visual attentional interventions are effective options for treating childhood dyslexia.

7.2.1 Temporal Processing Thresholds of Dyslexic and Neurotypical Children

In Chapter 4, thresholds of temporal processing were compared between dyslexic and neurotypical children (8-12 years, n = 54 per group) individually matched for age and intelligence. This was measured using two, four-alternative forced-choice achromatic flicker fusion threshold tasks modulated at low (5%) and high (75%) temporal contrast and designed to specifically target the M stream (Brown, Corner, Crewther, & Crewther, 2018; Brown, Peters, Parsons, Crewther, & Crewther, 2020). Significant group differences were obtained, with the dyslexic group displaying significantly lower ability to detect flicker at high temporal frequencies at low and high contrast than the neurotypical children, however, discriminant analysis using flicker threshold performances did not adequately differentiate the groups. Taken together, these results indicated that dyslexic children as a group show impaired temporal processing and neural recovery of the M pathway.

7.2.2 Temporal Processing Thresholds and Subtypes of Dyslexia

Chapter 4 additionally examined whether the temporal impairments found in the dyslexic sample were driven by a subset of participants. Two distinct dyslexic subgroups were obtained using cluster analysis – one characterized by significantly lower temporal frequency thresholds than neurotypicals (referred to as

'Magnocellular-Deficit' dyslexics; 53.7%), while the other group ('Magnocellular-Typical' dyslexics; 46.3%) had comparable thresholds to neurotypicals. Additionally, the Magnocellular-Deficit dyslexics and neurotypicals were dissociated with strong classification accuracy (79.3%) via flicker fusion threshold performances alone. Logistic regression of the identified subgroups further indicated that they were not associated with any of the four dyslexic subtypes (i.e., phonological deficit, rapid naming deficit, double deficit, no deficit) proposed by the double-deficit hypothesis (Wolf & Bowers, 1999). The findings extend on previous temporal threshold research (Brown et al., 2020; Chase & Jenner, 1993; McLean, Stuart, Coltheart, & Castles, 2011; Talcott et al., 1998) by showing significant heterogeneity in dyslexic flicker fusion performances, and more importantly, establishing the presence of two distinct subgroups – one characterized by impaired magnocellular-temporal processing thresholds and the other by threshold levels equivalent to those of neurotypicals.

7.2.3 Rapid Naming and Eye Movements in Young Readers

Chapter 5 investigated the pattern of eye movements recorded during rapid naming, as measures of the temporo-spatial placement of attentional engagement, shifting and rate of processing by the M stream. The aim was to determine whether eye movement patterns were significant predictors of rapid naming, independent of phonological awareness, and would be predictive of reading ability. This was assessed in a sample of children (aged 5 to 9 years; $n = 93$) with a range of reading abilities including some with dyslexia. The findings showed that, independently of phonological awareness, eye movements (fixation count and fixation duration) were highly predictive of children's rapid naming performance (92.8%), supporting the notion that rapid naming is not simply a measure of speed of phonological access, but reflects the "microcosm" of cognitive and attentional processes also required for reading. Both fixation count and fixation duration also predicted text reading accuracy (36.3%), comprehension (31.6%), and rate (36.2%) scores, and in predicting these text reading skills there was a high level of shared variance with RAN performance. Together these findings offer novel evidence that the rate and efficiency at which visual information can be attended and processed during fixations underpins RAN performance, with eye tracking providing a method to operationalize these processes and a way to further elucidate the RAN-reading relationship.

Chapter 5 also further investigated a subsample of the participants to compare the eye movement patterns of dyslexic children with aged-matched typical readers and younger typical readers matched for reading-level (n = 18 per group). Dyslexic children displayed significantly longer fixation durations and more fixation counts as compared with neurotypical children matched for age, though neither of these groups showed eye movement differences when compared to the younger neurotypical group matched for reading ability. No difference in saccade duration was found between groups. The findings indicate that those with dyslexia are generally less efficient in attending to and extracting information during fixations than same-aged peers during RAN tasks, despite being familiar with the stimuli. These results seem to imply that poor readers require greater attentional effort and longer fixations for the required cognitive processes of visual identification and access to the lexicon for naming. This highlights the increasing importance of investigating eye movement patterns in both reading research and clinical settings.

7.2.5 Action Video Game Training for Dyslexia

Chapter 6 expanded on the findings of the systematic review (Chapter 2) by attempting to elucidate the elements of dynamic attention that contribute most to the efficacy of visual attention training in dyslexia using AVGs. This was assessed in a sample of dyslexic children (aged 8 to 13 years; $n = 64$) by exploring whether AVG training effectiveness could be enhanced by increasing attentional and eye movement demands (i.e., enhanced AVG training) as compared to regular AVG training or a treatment-as-usual comparison group. The results showed that only the two AVG training groups significantly improved on reading accuracy, rate, comprehension and rapid naming tasks. Moreover, those with lower flicker fusion scores (i.e., slower temporal processing) before AVG training showed the greatest improvement in temporal processing, and improved low contrast flicker fusion significantly predicted reading accuracy improvements. Such findings are in line with past research showing that AVG training is an efficacious intervention option for dyslexia and provide novel evidence that rapid visual attentional processing is a mediating factor to this efficacy. In contrast to predictions, increasing attentional demands did not further enhance AVG efficacy. This finding suggested that enhanced AVG training may have required greater neural resources resulting in a higher level of eye movement difficulty for children to play and greater cognitive and motor fatigue, and thus consideration should be given to the level of game difficulty when selecting action games for use as an intervention for dyslexia.

Chapter 6 additionally assessed whether a shorter duration of training (10, 30-minute sessions) and a different action game (i.e., Fruit Ninja) than had been used in previous studies would also result in reading improvements. The findings showed that playing ‘Fruit Ninja’ for only five hours resulted in at least 6 months of improvement in reading accuracy, rate, comprehension and rapid naming in both AVG training groups. The moderate to large effect sizes (SMDs) found are comparable to past literature that included more than double the duration of training (12 hours) and employed a different game, suggesting that even brief AVG intervention can be of substantial benefit to those with dyslexia.

7.3 Theoretical and Clinical Implications of Findings

The current thesis has served to provide a deeper functional understanding of M pathway processing and the contribution of neural recovery thresholds to the rate of visual attention engagement and shifting in dyslexic children, not only in further elucidating their role in reading and dyslexia, but also in demonstrating that these processes are appropriate and effective targets of intervention for dyslexia. Summarized below are the overarching clinical and theoretical implications of the collective data presented in Chapters 2, 4, 5 and 6 of this thesis.

7.3.1 The Fundamental Role of Visual Attention and Magnocellular Processing in Reading

Findings of this thesis have led to an improved understanding of the importance of temporal processing thresholds of the M stream, and of the prevalence of such an impairment in dyslexic children. Indeed, impaired temporal frequency of the M pathway, as shown in Chapter 4, is the most likely explanation for the impaired rate of activation of visual attention (Barnard, Crewther, & Crewther, 1996), longer exposure time needed for accurate change detection, slower attentional shifting (Krause, 2015), and less efficient engagement and disengagement of attention and eye movements that are experienced by those with dyslexia (Krause, 2015; Lallier et al., 2010). Consistently, in Chapter 5, children with dyslexia demonstrated less efficient eye movements during rapid naming – longer fixation times and more fixations - as compared to same-aged peers. They also displayed slower rapid naming performances, itself a measure of visual-to-verbal processing speed (Denckla &

Rudel, 1974). Together, the findings of Chapters 4 and 5 highlight the role that an impaired rate of visual processing plays in dyslexia.

In examining the efficacy of visual attention interventions in dyslexia, through both systematically reviewing the current literature and conducting a randomized controlled trial (Chapters 2 and 6), this thesis has provided substantial evidence that visual attention training results in significant and meaningful improvements to reading skills in dyslexic children. Not only does this confirm the efficacy of visual attention training in dyslexia, but it also provides unequivocal evidence that M-driven visual attention plays an aetiological role in one type of dyslexia. Further research is needed to determine the extent to which it influences reading outcomes.

7.3.2 The Heterogeneity of Dyslexia

Findings from the research conducted for this thesis have also demonstrated that temporal processing impairments characterize a subtype of children with dyslexia, providing strong evidence that more consideration must be given to the heterogenous nature of reading disorders in both research and clinical practice. Indeed, while it is well known that phonological, orthographic and rapid naming subtypes exist (Boder, 1970; Castles & Coltheart, 1993; O'Brien, Wolf, & Levett, 2012; Wolf & Bowers, 1999), very few researchers have investigated the occurrence of subtypes in relation to magnocellular impairments that consequently impair speed of activation of visual attention (Bosse, Tainturier, & Valdois, 2007; Zoubrinetzky, Bielle, & Valdois, 2014). Investigations of the presence of such subtypes would likely address some of the criticisms of the magnocellular theory of dyslexia, particularly in regard to the variability in findings (Skottun, 2000). Moreover, it would provide additional and clinically translatable clarity about the nature and prevalence of visual attentional impairments, that could aid assessment and diagnosis of dyslexia.

7.3.3 Clinical Applicability of Visual Attention and Magnocellular Tasks

An important practical implication of the current findings is the need for visual attention and magnocellular tasks to be used clinically. To our knowledge, there is no well-established and well utilized clinical test of magnocellular-dorsal stream function. Yet, eye movements provide an efficient and non-invasive biobehavioural measure of moment-to-moment M pathway driven attentional processing, including the time to engagement and disengagement of attention, location of attentional focus, and the speed and duration of visual processing. Temporal processing thresholds as measured by flicker fusion tasks provide a simple, fast, and motor-free measure of M processing, which is known to be impaired in many neurodevelopmental disorders, not just dyslexia. The findings of the research reported in this thesis provide a clear demonstration that these tasks provide additional and rich information that, if used clinically, would enable better characterisation of the nature of an individual's reading impairment. Improved characterisation of the specific pattern of impairments experienced could then help guide the most appropriate interventions.

7.3.4 Deficits in Visual Attention – A Cause or Consequence of Dyslexia

The question of whether deficits in visuo-attentionally-driven skills reflect a cause or a consequence of reading failure remains intensely debated, with many critics arguing that reading enhances sensory and attentional processing and so visuo-attentional deficits in dyslexia may simply reflect reduced reading experience (Goswami, 2015). However, there is now strong evidence, including that from the current research, demonstrating such a causal role (Gori, Seitz, Ronconi, Franceschini, & Facoetti, 2016). In Chapter 5, a reading-level matched design was used to assess eye movements, and hence allocation of attention. Reading-level matched designs are acknowledged as one method upon which to establish causation by controlling for possible differences in reading experience. If children with reading disorders perform worse compared with younger reading-age matched neurotypical readers, this would be indicative of a causal role. As reported in Chapter 5, while dyslexic children displayed significantly longer fixation durations and more fixation counts compared with chronological-age matched neurotypical children, neither of these groups showed eye movement differences when compared to the younger reading-age matched neurotypical group. Though this result does not establish a causal role, it suggests a bidirectional relationship with both visual attention and reading each influencing each other. Furthermore, intervention studies are arguably the most robust research design in which to assess causation (Goswami, 2015) and, as reported in Chapters 2 and 6, training visual attention produced significant improvements in the reading skills in children with dyslexia, despite not directly training reading processes.

7.3.5 Identification of the Neurobiological Basis of Dyslexia

The current research findings provide key insights into the role of temporal processing and rate of visual attention in dyslexia and highlight that further research is urgently needed to determine a neurobiological definition and the neurobiological basis of dyslexia in order to inform improved diagnostic certainty. Indeed, many researchers and clinicians now solely attribute dyslexia as a phonologically based disorder, and diagnosis is often made purely on the basis of significantly reduced single word reading and/or phonological performance. Yet, this definition fails to adequately distinguish between those with a neurobiologically-based reading impairment (i.e., dyslexia) and those whose reading and phonological difficulties arise from other, often social, causes, such as inadequate education, lack of family support and generally low ability. As contended by Stein (2019), the phonological theory is not sufficient as it does not provide a neurobiological explanation for why phonological deficits occur. It also does not explain why some with dyslexia do not experience phonological impairment (O'Brien et al., 2012), why good phonological processing is not essential to good reading skill (Elhassan, Crewther, & Bavin, 2017), or why similar phonological impairments can also be found in children with language disorders who do not also have dyslexia (Ehrhorn, Adlof, Fogerty, & Laing, 2020). Not only does a temporally driven attention processing deficit provide a likely neurobiological basis, it cannot be a result of social factors, like inadequate education, and can explain phonological deficits (Rey, De Martino, Espesser, & Habib, 2002). If this is indeed the case, then flicker fusion tasks may provide a simple and non-invasive measure of temporal impairment indicative of a neurobiologically-based reading impairment as opposed to a social/education component. This then also raises questions about those with impaired reading that do not show a temporal impairment, such as one proposed subgroup (see Chapter 4). It may be that the reading impairments of the 'dyslexic' subgroup with unimpaired temporal processing are a result of social/educational causes and not neurobiologically-based. This would then help to explain much of the variability in findings reported in the literature into magnocellular functioning in dyslexia. Clearly further research is urgently needed to discover the neurobiological and physiological mechanisms that lead to dyslexics' particular kinds of reading problems.

7.4 Future Research Directions

The current research into M pathway temporal processing and consequential rate of visual attention in dyslexia has added to the current knowledge about dyslexia, but also prompts new directions of enquiry. The identification of a subgroup of dyslexics characterized by temporal visual processing impairments provides novel evidence of the fundamental role for the rate of M processing in reading and dyslexia. This temporally impaired dyslexic subgroup did not fit into previously identified subtypes (Wolf & Bowers, 1999). However, it is important to replicate our findings, and to clarify whether other factors or pattern of reading impairments may additionally characterize this subgroup. While temporal threshold manipulations, as compared to other proxies for M function properties such as low spatial frequency or low contrast performance, have received relatively less consideration to date, our findings also highlight the importance of including measures of temporal processing when assessing M processing in dyslexia.

Recording eye movements during RAN has proven to be an informative method of studying the RAN-reading relationship and for studying visual attention. What remains to be investigated is how the cognitive processes that also underlie rapid naming, relate to and influence individual eye movement variables during RAN. Moreover, while it is well known that the M pathway predominantly directs eye movements (Stein, 2003), it would be useful to explore the correlations between psychophysical tasks of M processing and eye movements.

The findings reported in this thesis present strong support for the use of interventions in dyslexia based on visual attention and its contribution to cognitive processes and at least for those children with dyslexia who show lower flicker fusion threshold scores. Nevertheless, there is a need for further, high quality studies that compare visual attention interventions to other established treatments for dyslexia in order to better elucidate which treatments are more or less efficacious for specific reading skills. Longer term follow-up studies are also needed to determine how long benefits are maintained, as are studies that investigate which dyslexic children may benefit the most from visual attention interventions and why. Future research should also consider comparing the effectiveness of several different AVGs as an intervention for dyslexia; this would not only help to determine whether different

AVGs are created equal but would also provide a list of games that clinicians could confidently recommend to their dyslexic clients. Although not the focus of this thesis, during the course of data screening and literature searching for the systematic review it was apparent that there is also a scarcity of investigations into visual attention training in adolescents and adults with dyslexia (Gori et al., 2016; Koen et al., 2017). Lastly, a meta-analysis is timely and warranted.

7.5 Conclusion

The research presented in this thesis has demonstrated that visual attention plays a fundamental role in dyslexia. Specifically, the findings show that children with dyslexia experience impairment in the rate of activation and shifting of visual attention as demonstrated via their less efficient eye movements. Some also show reduced visual temporal processing thresholds that are suggestive of slower neuronal recovery following rapid repetitive visual stimulation. The research reported in this thesis has additionally provided substantial evidence that training of visual attention processes can significantly benefit reading skills. Not only do these findings provide insights into the positive contribution that faster visual attentional processing makes to text reading, they also demonstrate that visual attention training is an effective intervention for dyslexia.

7.6 References

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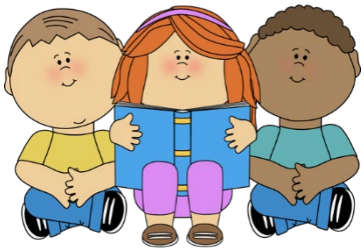
APPENDICES

Appendix A - Participant Information Sheet (Chapters 4 and 5)

Participant Information Statement

UNDERSTANDING THE ROLE OF VISUAL ATTENTION IN READING



Research Project supervised by Professor Sheila G. Crewther from the School of Psychology & Public Health at La Trobe University and funded by La Trobe University.

What is the purpose of the study?

Reading is an essential skill, which comes easily to some while others struggle to become confident and fluent readers, despite the most encouraging environments. This study aims to examine the complex visual and cognitive skills underlying fluent reading, with a particular focus on the role of visual attention. This knowledge will further our understanding of the skills underpinning fluent reading, and guide the development of teaching strategies in the future.

What will children be asked to do and how will the study be conducted?

1) Children will be asked to:

- Complete a number of short paper and computer tasks that measure reading, language, visual-attention, motor coordination, and memory skills known to be important in literacy development (Tasks are outlined in more details on pages 2-4).
- Children will also have their eye movement's video recorded during some of the above tasks.
- Children will complete the testing sessions individually at school during school hours, in the presence of another child and researcher. Testing will take place over two to three 30 minute sessions (A total of up to 1 hour 30 minutes).

Statement to be read to all participants:

"Would you like to play some activities and computer games with us? If you get tired to you can rest, or stop playing whenever you like."

What are the risks of this study?

There are no anticipated risks associated with participation in the study. There are no disadvantages, penalties or adverse consequences for not participating or for withdrawing from the research.

What are the benefits of this study?

All children who participate will be given small stationary items (e.g., stickers, pencils, rubbers) to thanks them for their time.

The major benefits to all participating children are vision and reading screening.

The research will also provide improved understanding of the factors underlying reading development, and hence how better to assist children to read.

How will the information collected be used?

Video recordings of eye position recorded by the eye tracker are only used immediately flowing the task to confirm the accuracy of the data and are not stored. The recordings only show each eye and not the participant's face, so as to ensure the anonymity of the participant is protected.

Where permission is granted by the parent/guardian, an individual child's outcomes may be communicated to their classroom teacher(s), literacy support teachers and/or principals.

If any visual anomalies are detected, the participant or parent/guardian of the participant will be notified by letter from the Chief Investigator (an Optometrist) and a referral suggestion to an appropriate specialist provided.

Participant's names, dates of birth, gender, schooling year level, and any relevant diagnoses (as provided by parents/guardians) are routinely recorded during data collection. Except where necessary for the circumstances outlined above, all identifiable personal information (e.g., participant names) will be removed from the data, and group data will be analysed. Data will be securely stored at the university, and disposed of by shredding when no longer in use. Data stripped of identifying personal information will be stored in electronic form for statistical analysis, and may be used in summary form, in research theses, books, journals, and presented and recorded at conferences. Individual data will never be identifiable except for abnormal vision screening results, in which a written referral will be given to the child to take home to their parent/guardian.

A summary of the group research outcomes will also be provided to your child's principal/director to disseminate. In past research this summary has been included in school newsletters for parents/guardians to read and/or communicated to teachers.

Steps to take if you would like to cancel your consent:

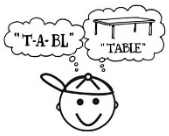
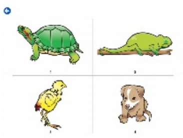
Please contact Chief Investigator, Professor Sheila Crewther, of La Trobe University within four weeks of the completion of your child's participation in the project by e-mail (s.crewther@latrobe.edu.au) or telephone (9479-1035) if you wish to withdraw your consent for your child's data to be used in this research project. Any questions regarding this project can also be directed to the investigator.

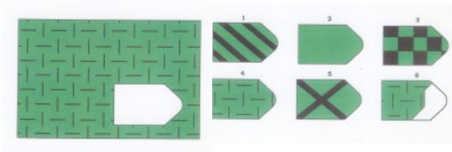
If you have any complaints or queries that the investigator has not been able to answer to your satisfaction, you may contact the Secretary, Human Ethics Committee, Research Services, La Trobe University, Victoria, 3086, ph: 03 9479 1443, e-mail: humanethics@latrobe.edu.au.

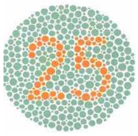
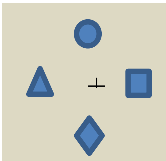
Who will be conducting the research?

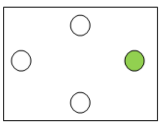
- *Professor Sheila G. Crewther*, Professor of Neuroscience, is the Chief Research Investigator
- *Jessica Peters*, PhD candidate from La Trobe University will oversee testing
- *Hayley Pickering,* PhD candidate from La Trobe University will oversee testing
- *Dr Alyse Brown,* La Trobe University
- *Dr Nahal Goharpey*, La Trobe University
- *Professor David Crewther,* La Trobe University
- *Laila Hugrass,* La Trobe University
- *Zena Elhassan,* La Trobe University
- *Rebecca Ravenhill,* La Trobe University
- *Jessica Sawan,* La Trobe University
- *Larissa Roman,* La Trobe University
- *Rowena Bicknell,* La Trobe University
- *Kate Mellody,* La Trobe University

What tasks will my child be asked to complete?

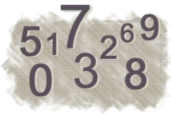
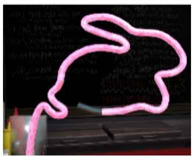
Task	Procedure
LANGUAGE TASKS	
Phonological Awareness 	Children will be asked to blend individual sounds together (e.g. 'b' and 'at' come together to make 'bat'), remove an individual sound (e.g. remove 'steam' from 'steamboat'?), and identify the first and last sound of a word. These tasks assess the child's phonological awareness. They are expected to take up to 10 minutes in total.
Listening Comprehension Task 	Children will be asked to match a spoken word with a picture of an object, action or concept as well as name the object, action, or concept that is shown in a picture. This task assesses the child's language skills. It is expected to take 5 minutes in total.

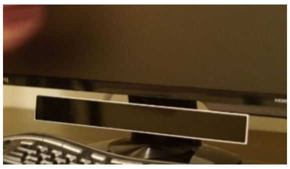
<table>
<tr><th colspan="2">PROBLEM SOLVING TASK</th></tr>
<tr><td>Visual Problem Solving
</td><td>Children will be shown figures that have a piece missing, such as that shown on the left. They will be asked to select the missing piece of the puzzle from 6 possible choices. Children’s eye movements will be recorded during this task.

This task assesses visual problem solving ability. It will take around 5 minutes to complete.</td></tr>
<tr><th colspan="2">VISUAL TASKS</th></tr>
<tr><td>Visual Screening

</td><td>Children will be asked to look at and label some letters, shapes and colours. This will indicate whether children have any basic visual abnormalities. This will take up to 5 minutes.</td></tr>
<tr><td>Visual Change Detection
</td><td>Children will view two images containing a number of objects displayed very quickly one after the other. The second image may be exactly the same as the first, or contain one different object. The child will be asked to indicate whether the second image was the same or different. This assesses the child’s ability to detect change in visual stimuli. It will take around 3 minutes.</td></tr>
<tr><td>Visual Inspection Time
</td><td>Children will view a picture of a rainbow facing one of four directions displayed very quickly. Children will then be asked to indicate which direction the rainbow was facing.

This assesses the child’s ability to rapidly identify visual stimuli. It takes around 3 minutes.</td></tr>
<tr><td>Flicker Task
</td><td>Children will view stimuli and will be asked to decide which of four options they saw across a number of trials.

This assesses a child’s ability to detect rapid visual information and will take up to 5 minutes to complete.</td></tr>
</table>

MEMORY TASKS	
Memory 	Children will view/hear information, and then will be asked to recall this information. Children will also be asked to view pictures on a screen and respond when they see a target image directly after another target image. These tasks provide a measure of children's ability to hold information in memory and recall it.
MOTOR TASKS	
Slurp 	Slurp is an iPad app that asks children to trace shapes with their fingers rapidly and accurately. The activity assesses hand-eye coordination and will take around 2 minutes to complete.
READING TASKS	
Rapid Naming  	Children will be asked to name familiar items on a computer screen, 'reading' the screen as fast as they can from left to right, top to bottom. Children's eye movements will be recorded by the computer during this task. The task measures the child's ability to retrieve and speak a letter/picture's name. It takes around 2 minutes to complete.
Reading Ability	Children will be asked to read lists of words, and read and answer questions about a number of short stories, using texts of increasing difficulty up to the child's comfortable reading level. These tests will measure reading accuracy, reading comprehension and reading rate. It will take between 5 and 10 minutes to complete.
EYE MOVEMENTS	

Eye Tracker 	Children's eye movements will be video recorded during some of the tasks by an eye tracking bar at the bottom of the computer screen. Children will be able to use a chin rest to help keep still for the task.

Notes:

- *Tasks designed to increase in difficulty will stop at a comfortable level for the child.*
- *If a task seems inappropriate for a child, they will not be asked to do it.*

Appendix B – Consent Form (Chapters 4 and 5)

CONSENT FORM

UNDERSTANDING THE ROLE OF VISUAL ATTENTION IN READING

I ________________________________ (the legal guardian of the participant) have read and understood the **Participant Information Statement and Consent Form** and any questions I have asked have been answered to my satisfaction.

I agree that ______________________________ who was born on ____/___/____ for whom I am legal guardian may participate in the project, realising that I may withdraw my consent at any time, up to four weeks following the completion of participation in the research project.

I agree that research data provided by me or with my permission during the project may be included in a thesis, book, presented and recorded at conferences, and published in journals on the condition that neither the participant's name nor any other identifying information is used. Specifically:

1. Y / N — I give permission for my child to participate in the 2-3 sessions of short computer and paper tasks, as outlined in the information statement.

2. Y / N — I give permission for my child's eye movements to be video recorded, as outlined in the information statement.

3. Y / N — I give permission for researchers to discuss my child's assessment with their teacher(s), and/or principals.

4. Y / N — Please indicate whether your child has a **<u>formally</u>** diagnosed developmental or medical condition (e.g., Epilepsy, Autism, Dyslexia, ADHD). If yes, please specify: ____________________________

5. Y / N — Please indicate if your child primarily speaks English at home. (if other than English, please specify): ____________________________

Name of Participant (block letters): ____

Grade Level: _____

Name of Parent/ Guardian (block letters): ____

Parent Signature: ________________________________ **Date: ____/___/_______**

Name of Investigator (block letters): SHEILA CREWTHER

Investigator Signature: **Date: ____/____/______**

Appendix C - Participant Information Sheet (Chapter 6)

Participant Information Statement

UNDERSTANDING THE ROLE OF VISUAL ATTENTION IN READING

Research Project supervised by Professor Sheila G. Crewther from the School of Psychology & Public Health at La Trobe University and funded by La Trobe University.

What is the purpose of the study?

Reading is an essential skill, which comes easily to some while others struggle to become confident and fluent readers, despite the most encouraging environments. This study aims to examine the complex visual and cognitive skills underlying fluent reading, with a particular focus on the role of visual attention. This knowledge will further our understanding of the skills underpinning fluent reading, and guide the development of teaching strategies in the future.

What will children be asked to do and how will the study be conducted?

Children will be invited to participate in an experimental game-based intervention program designed to train aspects of attention and literacy. As part of this, they will be asked to:

- Complete a number of short paper and computer tasks that measure reading, language, visual-attention, motor coordination, and memory skills known to be important in literacy development (Tasks are outlined in more details on pages 3-4) at three time points approximately three weeks apart each.
- The first session will be approximately 1 hour (2 x 30 minute sessions), and the two subsequent sessions will each be approximately 40 minutes each.
- Between the second and third time point, children will be invited to participate in 2 weeks of experimental game-based intervention. The intervention will consist of 10 thirty-minute training sessions across the 2-week period. Training will occur at school during school hours in small groups of four children.
- The maximum time commitment, including all the assessment and training sessions, is estimated to not be more than 8 hours in total.

Statement to be read to all participants:

"Would you like to play some activities and computer games with us? If you get tired to you can rest, or stop playing whenever you like."

What are the risks of this study?

There are no anticipated risks associated with participation in the study. There are no disadvantages, penalties or adverse consequences for not participating or for withdrawing from the research.

What are the benefits of this study?

All children who participate will be given small stationary items (e.g., stickers, pencils, rubbers) to thanks them for their time.

The major benefits to all participating children are school based reading screening. For those who participate in the experimental game-based training they may see improvements in areas of attention and literacy.

The research will also provide improved understanding of the factors underlying reading development, and hence how better to assist children to read.

How will the information collected be used?

Video recordings of eye position recorded by the eye tracker are only used immediately flowing the task to confirm the accuracy of the data and are not stored. The recordings only show each eye and not the participant's face, so as to ensure the anonymity of the participant is protected.

Where permission is granted by the parent/guardian, an individual child's outcomes may be communicated to their classroom teacher(s), literacy support teachers and/or principals.

If any visual anomalies are detected, the participant or parent/guardian of the participant will be notified by letter from the Chief Investigator (an Optometrist) and a referral suggestion to an appropriate specialist provided.

Participant's names, dates of birth, gender, schooling year level, and any relevant diagnoses (as provided by parents/guardians) are routinely recorded during data collection. Except where necessary for the circumstances outlined above, all identifiable personal information (e.g., participant names) will be removed from the data, and group data will be analysed. Data will be securely stored at the university, and disposed of by shredding when no longer in use. Data stripped of identifying personal information will be stored in electronic form for statistical analysis, and may be used in summary form, in research theses, books, journals, and presented and recorded at conferences. Individual data will never be identifiable except for abnormal vision screening results, in which a written referral will be given to the child to take home to their parent/guardian.

A summary of the group research outcomes will also be provided to your child's principal/director to disseminate. In past research this summary has been included in school newsletters for parents/guardians to read and/or communicated to teachers.

Steps to take if you would like to cancel your consent:

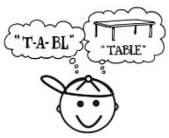
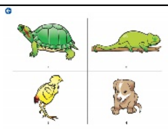
Please contact Chief Investigator, Professor Sheila Crewther, of La Trobe University within four weeks of the completion of your child's participation in the project by e-mail (s.crewther@latrobe.edu.au) or telephone (9479-1035) if you wish to withdraw your consent for your child's data to be used in this research project. Any questions regarding this project can also be directed to the investigator.

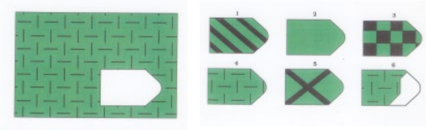
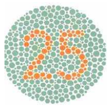
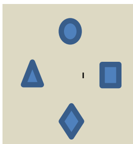
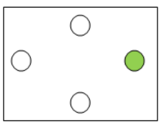
If you have any complaints or queries that the investigator has not been able to answer to your satisfaction, you may contact the Secretary, Human Ethics Committee, Research Services, La Trobe University, Victoria, 3086, ph: 03 9479 1443, e-mail: humanethics@latrobe.edu.au.

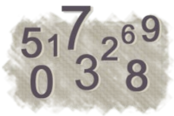
Who will be conducting the research?

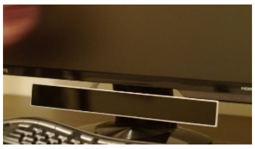
- *Professor Sheila G. Crewther*, Professor of Neuroscience, is the Chief Research Investigator
- *Jessica Peters*, PhD candidate from La Trobe University will be responsible for overseeing testing
- *Dr Nahal Goharpey*, Associate Lecturer (PhD) at La Trobe University
- *Hayley Pickering,* PhD candidate from La Trobe University, Melbourne
- *Professor David Crewther,* La Trobe University
- Laila Hugrass, La Trobe University
- *Cansu Alihos,* La Trobe University
- *Zena Elhassan,* La Trobe University
- *Rebecca Ravenhill,* La Trobe University
- *Jessica Sawan,* La Trobe University
- *Larissa Roman,* La Trobe University

What tasks will my child be asked to complete?

Task	Procedure
LANGUAGE TASKS	
Phonological Awareness 	Children will be asked to blend individual sounds together (e.g. 'b' and 'at' come together to make 'bat'), remove an individual sound (e.g. remove 'steam' from 'steamboat'?), and identify the first and last sound of a word. These tasks assess the child's phonological awareness. They are expected to take up to 10 minutes in total.
Listening Comprehension Task 	Children will be asked to match a spoken word with a picture of an object, action or concept as well as name the object, action, or

	concept that is shown in a picture. This task assesses the child's language skills. It is expected to take 5 minutes in total.
PROBLEM SOLVING TASK	
Visual Problem Solving 	Children will be shown figures that have a piece missing, such as that shown on the left. They will be asked to select the missing piece of the puzzle from 6 possible choices. Children's eye movements will be recorded during this task. This task assesses visual problem solving ability. It will take around 5 minutes to complete.
VISUAL TASKS	
Visual Screening 	Children will be asked to look at and label some letters, shapes and colours. This will indicate whether children have any basic visual abnormalities. This will take up to 5 minutes.
Visual Change Detection 	Children will view two images containing a number of objects displayed very quickly one after the other. The second image may be exactly the same as the first, or contain one different object. The child will be asked to indicate whether the second image was the same or different. This assesses the child's ability to detect change in visual stimuli. It will take around 3 minutes.
Visual Inspection Time 	Children will view a picture of a rainbow facing one of four directions displayed very quickly. Children will then be asked to indicate which direction the rainbow was facing. This assesses the child's ability to rapidly identify visual stimuli. It takes around 3 minutes.
Flicker Task 	Children will view stimuli and will be asked to decide which of four options they saw across a number of trials. This assesses a child's

	ability to detect rapid visual information and will take up to 5 minutes to complete.
	MEMORY TASKS
Memory 	In one task, children will view/hear a list of numbers, and then will be asked to recall these numbers in either forward or reverse order. Children will also be asked to view pictures on a screen and respond when they see a target image directly after anoth target image. These tasks provide a measure of children's ability to hold information in memory. They will take up to 3 minutes to complete per task.
	READING TASKS
Rapid Naming 	Children will be asked to name familiar items on a computer screen, 'reading' the screen as fast as they can from left to right, top to bottom. Children's eye movements will be recorded by the computer during this task. The task measures the child's ability to retrieve and speak a letter/picture's name. It takes around 2 minutes to complete.
Reading Ability 	Children will be asked to read lists of words, and read and answer questions about a number of short stories, using texts of increasing difficulty up to the child's comfortable reading level. These tests will measure reading accuracy, reading comprehension and reading rate. It will take between 5 and 10 minutes to complete.
Reading Fluency 	Children will be asked to read a story rapidly displayed a few words at a time. This task measures reading fluency. They will be asked how much they enjoyed the task afterwards. This task takes up to 3 minutes.

EYE MOVEMENTS	
Eye Tracker 	Children's eye movements will be video recorded during some of the tasks by an eye tracking bar at the bottom of the computer screen. Children will be able to use a chin rest to help keep still for the task.
READING TRAINING	
Computer Game Training 	Eligible children will be asked to play computer games designed to improve aspects of literacy by training the rapid focus of attention. Research has shown that similar games can improve aspects of attention and literacy.

Notes:

- *Tasks designed to increase in difficulty will stop at a comfortable level for the child.*
- *If a task seems inappropriate for a child, they will not be asked to do it.*

Appendix D - Consent Form (Chapter 6)

CONSENT FORM
UNDERSTANDING THE ROLE OF VISUAL ATTENTION IN READING

I ________________________________ (the legal guardian of the participant) have read and understood the **Participant Information Statement and Consent Form** and any questions I have asked have been answered to my satisfaction.

I agree that ______________________________ who was born on ____/___/____ for whom I am legal guardian may participate in the project, realising that I may withdraw my consent at any time, up to four weeks following the completion of participation in the research project.

I agree that research data provided by me or with my permission during the project may be included in a thesis, book, presented and recorded at conferences, and published in journals on the condition that neither the participant's name nor any other identifying information is used.

Specifically:

1. Y / N — I give permission for my child to participate in the computer-based intervention training (2 weeks) and participate in 4 sessions of short computer and paper assessment tasks, as outlined in the information statement.

2. Y / N — I give permission for my child's eye movements to be video recorded, as outlined in the information statement.

4. Y / N — I give permission for researchers to discuss my child's assessment with their teacher(s), and/or principals.

5. Y / N — Please indicate whether your child has a **formally** diagnosed developmental or medical condition (e.g., Epilepsy, Autism, Dyslexia, ADHD). If yes, please specify: ____________________________

6. Y / N — Please indicate if your child primarily speaks English at home.
(if other than English, please specify): ____________________________

Name of Participant (block letters): ____
Grade Level: _____
Name of Parent/ Guardian (block letters): ____
Parent Signature: _______________________________ Date: ____/___/_______

Name of Investigator (block letters): SHEILA CREWTHER

Investigator Signature: **Date: ____/____/______**

Appendix E – Withdrawal of Consent Form

WITHDRAWAL OF CONSENT FOR USE OF DATA FORM

UNDERSTANDING THE ROLE OF VISUAL ATTENTION IN READING

I, ___________________________ (the legal guardian of the participant), wish to WITHDRAW my consent to the use of data arising from my child's participation. Data arising from my child's participation must NOT be used in this research project as described in the Information and Consent Form. I understand that data arising from my child's participation will be destroyed provided this request is received within four weeks of the completion of my child's participation in this project. I understand that this notification will be retained together with my consent form as evidence of the withdrawal of my consent to use the data I have provided specifically for this research project.

Name of Participant (block letters): ____

Name of Parent/ Guardian (block letters): ____

Parent Signature: ____________________________________ Date: ____/___/_______

Name of Investigator (block letters): SHEILA CREWTHER

Investigator Signature: Date: ____/____/______

Appendix F – Chapter Two: Publication

Neuroscience and Biobehavioral Reviews 100 (2019) 58–76

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Review article

Efficacy of dynamic visuo-attentional interventions for reading in dyslexic and neurotypical children: A systematic review

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ABSTRACT

Dyslexia is associated with phonological and visuo-attentional deficits. Phonological interventions improve word accuracy and letter-sound knowledge, but not reading fluency. This systematic review evaluated the effectiveness of dynamic computerized visuo-attentional interventions aimed at improving reading for dyslexic and neurotypical children aged 5–15. Literature searches in Medline, PsycINFO, EMBASE, Scopus, ERIC, PubMed, Web of Science, and Cochrane Library identified 1266 unique articles, of which 18 met inclusion criteria (620 participants; 91.40% dyslexic). Three types of visuo-attentional interventions were identified. Results show that visual perceptual training ($n = 5$) benefited reading fluency and comprehension, visually-based reading acceleration programs ($n = 8$) improved reading accuracy and rate, and action video games ($n = 5$) increased rate and fluency. Visuo-attentional interventions are effective options for treating childhood dyslexia, improving reading generally equal to or greater than other strategies. Initial evidence indicates that visuo-attentional interventions may be efficacious in different orthographies, and improve reading for at least two months after intervention. Larger sample interventions on a wider range of reading skills with follow-up assessment are needed to further clarify their effectiveness.

1. Introduction

Developmental Dyslexia (DD) is a neurodevelopmental disorder characterised by problems in learning to read and affects 10% of the population worldwide (American Psychiatric Association., 2013). Individuals with DD experience deficits in their ability to decode letters and sounds, and show impaired accuracy and word recognition, consequentially resulting in significant educational and occupational disadvantage throughout the lifespan (Lyon et al., 2003) despite adequate intelligence and education.

Substantial research over the last fifty years has demonstrated that deficits in reading are associated with both phonological processing (Snowling, 2001; Vellutino, 1979, 1987; Vellutino et al., 2004; Wagner and Torgesen, 1987; Wagner et al., 1994) and visuo-attentional mechanisms in children and adults with DD (Badcock et al., 2008; Barnard et al., 1996, 1998; Crewther et al., 1999; Facoetti and Molteni, 2001; Gori et al., 2016; Lovegrove et al., 1980; Lovegrove and Brown, 1978; Rutkowski et al., 2003; Stein, 2001, 2003, 2018; Stein et al., 1988; Stein and Walsh, 1997), highlighting that DD is a multifaceted, heterogeneous disorder (Menghini et al., 2010).

Since Vellutino (1979), remediation programs focusing on improving phonological processing, known to be one of the strongest predictors of word reading accuracy (Mann and Wimmer, 2002), have been frequently used. Although recent research indicates that such programs are ineffective in up to one third of children (Whiteley et al., 2007), and when successful, reading outcomes are often in terms of single word and pseudoword reading accuracy and letter-sound knowledge, rather than text reading fluency (i.e., the ability to read text rapidly, accurately, and with prosody) and comprehension (see meta-analyses by Bus, 1999; McArthur et al., 2012). Furthermore, these remediation strategies are resource-demanding, are more beneficial for those learning to read rather than more established readers, and typically reduce the degree of reading difficulty rather than normalize it (Gabrieli, 2009). More recent evidence from children with DD (aged 6–8 years) also shows that around 38–53% do not present with phonological deficits (O'Brien et al., 2012), necessitating investigations into alternate remediation options.

More recently, research in the area of reading remediation has shifted in emphasis to multiple investigations of non-phonological reading interventions which target visuo-attentional deficits and visuo-attentional mechanisms. Such remediation programs are based on literature showing that spatially and temporally dependent processes,

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0149-7634/

such as dynamic visuo-attention, rapid naming/word recognition, and eye movements, are most predictive of reading rate and fluency (Al Dahhan et al., 2014; Elhassan et al., 2017, 2015; Franceschini et al., 2012; Georgiou et al., 2008; Poulsen et al., 2015). Thus, visuo-attentional interventions may address the limitations of current dyslexia interventions by targeting other reading skills, such as rate and fluency (e.g., Franceschini et al., 2013). Such remediation evidence would provide further validation that visuo-attentional deficits are contributing factors of DD (Facoetti et al., 2003; Franceschini et al., 2012, 2013; Gori et al., 2016). Therefore, a thorough review of the current state of research into these types of visuo-attentional interventions for reading is timely and necessary.

1.1. Visuo-attentional deficits in dyslexia

Research into DD has reliably identified impairments across visuo-attentional mechanisms. The orienting and focusing of visuospatial attention, often described as the 'spotlight of attention', is impaired in dyslexia and results in inefficiencies in selectively extracting and processing the spatial relationship of visual information from a specific region of space within the visual field (Facoetti et al., 2000b; Treisman, 1988). Such individuals demonstrate a more distributed/diffused mode of attention, and are impaired on tasks of focused spatial attention, visual search and visual (peripheral) cuing (Facoetti et al., 2003, 2000a; Facoetti et al., 2000b; Franceschini et al., 2012; Liu et al., 2018; Pammer et al., 2004; Vidyasagar and Pammer, 2010). Those with DD also demonstrate impairments in the rapid engagement of attention, referred to as 'sluggish attentional shifting', which results in abnormal temporal, crowding and lateral masking performances, and can be used to predict poor reading outcomes in young children (Facoetti et al., 2010; Franceschini et al., 2018; Hari and Renvall, 2001). Interestingly, considerable evidence indicates that deficits in temporal processing and attention shifting are not exclusive to the visual modality, but are found for transient auditory and cross-modal information (Auditory timing deficits are beyond the purpose of this review, but see Au and Lovegrove, 2001; Casini et al., 2018; Stein, 2018).

Individuals with DD, including pre-reading children at risk of DD, demonstrate deficits in visual motion perception. This results in reduced proficiency to infer the speed and direction of elements of visual stimuli on tasks such as motion coherence and direction discrimination (Albright and Stoner, 1995; Boets et al., 2011; Cornelissen et al., 1995; Gori and Facoetti, 2014; Gori et al., 2016; Kevan and Pammer, 2009; Mascheretti et al., 2018; Stein, 2014). Similarly, dyslexics show visual temporal processing impairments, displaying higher gap-detection thresholds to visual stimuli presented sequentially and rapidly (Au and Lovegrove, 2001; Martos and Marmolejo, 1993; Wang and Yang, 2018), longer visual persistence to low-spatial-frequency stimuli, such as measured by contrast sensitivity tasks (Slaghuis and Lovegrove, 1985), as well as slower recognition and correct visual sequencing of letters (Ozernov-Palchik et al., 2017; Stein and Walsh, 1997). Inefficiencies in attentionally-driven eye movements are also often evident in those with DD during both reading and non-reading tasks (Al Dahhan et al., 2014, 2016; Biscaldi et al., 2000; Rayner et al., 2013; Stein and Fowler, 1981). Many dyslexic readers also experience visuoperceptual anomalies - displacing and inverting letters within a word, causing words to appear moving, distorted, crowded, or overlapping (Boets et al., 2007; Facoetti et al., 2003).

What is imperative to all these attentional mechanisms is the dynamic, transient processing of rapidly presented visual information. Unequivocally, when reading text one must sequentially, spatially and temporally select the word to be read; successively and rapidly moving the eye and the attentional spotlight (Laycock and Crewther, 2008). These processes are often linked to the faster subcortical magnocellular (M) stream that is responsive to high temporal and low spatial frequencies and responsible for stabilizing and directing eye movements, multisensory selective attention, and motion processing (Bruce et al., 1985; Stein, 2001, 2003, 2018; Stein and Walsh, 1997). Therefore, the deficits that those with DD show on these tasks are thought to be attributed to an underlying sensitivity weakness of the transient M system, specifically of the dorsal stream (Crewther et al., 1996; Gori and Facoetti, 2014; Laycock et al., 2012; Stein, 2001, 2018; Stein and Walsh, 1997; Vidyasagar and Pammer, 2010). In contrast, those with DD do not show impairments in static visuo-attention (Barnard et al., 1998; Hansen et al., 2001; Lovegrove et al., 1982). Thus not unexpectedly, past interventions that have focussed on static visuo-attention have not been effective (see Kavale, 1984).

1.2. Can dynamic visuo-attention interventions improve reading?

In order for interventions to adequately remediate the dynamic visuo-attention impairments found in DD, maximal loading of spatial and/or temporal processing of visual information, appropriate to the ability of the individual, would be necessary. This would only be feasible through computerised delivery. In fact, there have been several recent reports on improving reading through the use of computerized visual programs that heavily engage spatial and/or temporal attention, including action video games and direction discrimination training, and these have demonstrated success (Franceschini et al., 2013; Lawton, 2004). Importantly, they are examples of active interventions (as opposed to passive interventions) that aim to achieve ongoing cognitive improvement. While existing visuo-attentional intervention studies appear to vary widely in terms of population age (i.e., pre-readers through to adults), the majority have focused on primary school aged children up to age 14 or 15 years (e.g., Facoetti et al., 2003; Gori et al., 2016; Lorusso et al., 2011). This age range is when intervention is potentially of greatest benefit as children are undergoing rapid neural and developmental periods and attention networks are still maturing (Crewther et al., 1996; Klaver et al., 2011; Kolb, 2009; Langrová et al., 2006; McIntosh et al., 2006). While a number of papers have reported on the usefulness of similar types of interventions for reading in unselected populations or other clinical populations (e.g., Dodick et al., 2017; Kirk et al., 2017), this review is specific to studies of dyslexic children compared to typically developing readers. This criterion was set to establish the role of visuo-attention and efficacy of its intervention in DD.

Thus, the objective of this systematic review is to evaluate the efficacy of active, computerized visuo-attentional interventions that do not include any direct phonological input on the reading of typical and dyslexic children aged 5–15 years. Five years is the age when formal education usually begins and when reading can start to be typically assessed and so it is appropriate to start there. Reporting of the systematic review followed PRISMA guidelines (see supplementary document Table S1 for PRISMA checklist; Moher et al., 2009). Table 1 provides a list of abbreviations used throughout the text of the review; those used in a specific table are identified below the table.

Table 1
Abbreviations.

DD	Developmental Dyslexia
M stream/system	Magnocellular stream/system
ROBINS-I	Risk of Bias in Non-randomised Studies of Interventions
AVG	Action Video Game
Non-AVG	Non-action video games
RAP	Reading Acceleration Program
VPT	Visual Perceptual Training
VHSS	Visual Hemispheric Specific Stimulation
DDT	Direction Discrimination Training
TDT	Texture Discrimination Training
SMD	Standard mean difference
eSMD	Estimate Standard mean difference

2. Method

2.1. Search strategy

Prior to performing the review, a complete protocol was pre-specified and registered at PROSPERO (registration number CRD42017060282; Initial registration dated 27/03/2017; Peters et al., 2017).

Studies were identified through electronic database searching in Medline (Ovid, 1946 to present), PsycINFO (Ovid, 1806 to present), EMBASE (Ovid), and adapted for Scopus (Elsevier), ERIC (Proquest), PubMed, Web of Science (ISI), and Cochrane Library, for all available years. The final database search was run on 28 August 2018. In addition, hand searching ('Snowballing') was also conducted from the reference lists of those studies that met inclusion criteria.

The following search strategy was conducted in MEDLINE (OVID) using MeSH terms and Keywords:

1 (visual or visuo* or vision or attention* or perceptual or eye movement* or fixation* or saccad* or computer or video) adj4 (game* or gaming or treatment or therap* or train* or program* or intervention* or exercis* or remediat*).mp
2 Video Games/
3 3 1 or 2
4 Dyslexia/
5 Dyslexi*.mp
6 (Reading or learning) adj3 (disorder* or disabilit* or difficulty or difficulties or impairment).mp
7 (reader* or reading).mp
8 4 or 5 or 6
9 7 and 8
10 3 and 9

2.2. Study selection

All studies investigating active computerized interventions which target dynamic visuo-attentional processes to improve reading in children aged 5–15 years were included in the current review. This included, but was not limited to, interventions targeting visuo- attention/processing/perception, or attentionally-driven eye movements. Further, only neurotypical readers and those with developmental dyslexia were included. Studies that included a 'dyslexic' population were required to provide sufficient information to substantiate that participants met criteria for dyslexia. That is, only studies explicitly identifying children as having clinical dyslexia (or an appropriate alternative terminology, i.e., specific learning disorder in reading, reading disorder), that provided the diagnostic criteria employed (e.g., DSM-5, ICD-10, documented diagnosis, reading ability > 2SD below age norms), and indicated that all other diagnoses had been excluded. Information about the diagnostic criteria employed by each study is displayed in Table 4. Studies that included typically developing children were similarly required to indicate that all other diagnoses were screened and excluded. Therefore, studies that did not explicitly exclude children with neurological, neurodevelopmental, or uncorrected visual disorders, other than dyslexia, or separately group them (to permit data extraction of relevant group information) were excluded. Studies were included if they measured one or more of the following reading outcomes at either a word or text level - reading rate, accuracy, comprehension, and/or fluency. Further, studies were excluded if they did not separately analyse the efficacy of computerised visuo-attentional training when included in a broader intervention that actively trained other skills (e.g., working memory training); or if they did not include a control or comparison group. Included studies were required to be quantitative and published in English. Case studies and qualitative studies were excluded. There was no limit placed on year of publication.

The eligibility assessment process was performed independently by two reviewers (JP and LD) using the data management service, Covidence (Veritas Health Innovation, 2019). The reviewers first independently screened the title and abstract of each identified record to determine whether to accept or reject the study for further review. The reviewers then independently reviewed the method and results section of each potentially relevant study to determine whether to accept or reject the study based on the pre-specified inclusion/exclusion criteria. Disagreements at each stage were settled by a co-author (SC). Where the full-text of a study was not available, contact with the corresponding author was attempted though email. The decision to reject a study was recorded using a custom hierarchy of 8 exclusion reasons:

1 Not written in English
2 Not an intervention study
3 Study design did not meet criteria (Study was qualitative, a case study, or did not include a control/comparison group)
4 Population did not meet criteria (Study did not include a dyslexic and/or typical population aged 5–15 years)
5 Intervention did not meet criteria (intervention was not dynamic, computerised, and/or visuo-attention-based)
6 Outcomes of interest not measured (Study did not measure reading outcomes)
7 Not enough information provided (e.g., published conference presentations)
8 Study did not satisfy risk of bias criteria (see Section 2.4)

Potentially relevant studies were excluded if the full-text could not be located, or if there was insufficient information to determine if the study met all inclusion criteria and contact with the corresponding author was unsuccessful or the author was unable to provide the requested information. A list of visuo-attentional intervention studies that did not meet the strict inclusion criteria (e.g., population age, other diagnoses not excluded) but are relevant to the area of visuo-attentional interventions has been provided in the supplementary document (See Table S3).

2.3. Data collection process

A data extraction template was created through Covidence (Veritas Health Innovation, 2019). The template was pilot-tested and refined as needed. Each reviewer extracted data on half of the included studies, with the other reviewer checking the extracted data.

From each included study, information was extracted on:

1 Study information (country, language, date of study, setting)
2 Participant information (total number, diagnostic criteria, age)
3 Intervention (intervention groups, number of participants allocated to each intervention, intervention description, intervention duration)
4 Outcomes (outcomes and time points, outcome definition, unit of measurement)
5 Results (missing participants, summary data for each intervention group [mean and SDs, standard mean difference of change, *p*-value])
6 Miscellaneous (key results and conclusions provided by the study authors)

As data were extracted, a uniformity of terms was applied to the outcome measures so as to allow easier comparisons. For example, the term reading rate was applied for all measures of speed of reading, reading fluency was used for any measure that combined accuracy and speed of reading, and whether reading measures were at a word or text level were delineated. If an included study had missing data (i.e., standard mean difference of change; SMD), contact was attempted with the corresponding author. Where the SMD was not reported or not provided by the author upon request, an estimate of the SMD was calculated, where possible, using guidelines reported in chapter 7.7 of the Cochrane Handbook for Systematic Reviews of Interventions Version 5.1.0 (Higgins and Green, 2011).

2.4. Risk of bias in individual studies

Quality assessment of included randomized studies utilized the Cochrane Collaboration's Tool for Assessing Risk of Bias (chapter 8.5) reported in the Cochrane Handbook for Systematic Reviews of Interventions (Higgins and Green, 2011). The Risk of Bias in Non-randomised Studies-of Interventions (ROBINS-I) assessment tool was used as the quality assessment of included non-randomised studies (Sterne et al., 2016). Assessments were completed at the study level and were conducted independently by two reviewers (JP and LD). Where the two reviewers disagreed on the level of risk for a domain, a co-author (SC) was consulted to determine the appropriate risk of bias level. Where insufficient information was available to assess the risk of bias for a domain, the corresponding authors were contacted for further information.

As the two Risk of Bias tools used had distinct criteria, the decision to exclude studies of insufficient quality needed to be based on domains comparable across the tools and study designs. Therefore, studies were excluded if they displayed High/Critical (Cochrane/ROBINS-I respectively) levels of risk for their intervention/group descriptions, deviations from interventions, and reporting of results. Intervention/group description and deviations from intervention were assessed under the ROBINS-I 'classification of interventions' and 'deviations from intended interventions' domain respectively and for Cochrane, under the 'other sources of bias' domain, while reporting of results was assessed under the ROBINS-I 'reported result' domain and Cochrane 'selective reporting' domain. It is important to note that the Risk of Bias assessments apply only to how well study results assessed the outcomes of interest to the current systematic review, irrespective of the objectives of the original study.

3. Results

3.1. Risk of bias within studies

Risk of bias assessments for the non-randomised (ROBINS-I) and randomised (Cochrane Risk of Bias Assessment) interventions were conducted to ascertain if the studies satisfied the final inclusion criteria (exclusion reason 8) and determine the study quality in relation to the objective of the current review (see Tables 2 and 3). Two non-randomised studies displayed critical risk of bias in each of the 'classification of interventions', 'deviations from intended interventions' and 'reported result' domains when reviewed in line with the objectives of the current review and were therefore excluded from further review (see supplementary document Table S3 for further information; Lawton, 2007, 2011).

3.2. Study selection

Database and hand searching identified a total of 2309 citations, of which 1266 were unique citations (duplicates $n = 1043$). Following title and abstract screening, 252 were identified as eligible for full-text review, while 1014 were removed as they clearly did not meet inclusion criteria. Full-text review of the remaining articles excluded 232 that did not meet inclusion criteria. Eight were not written in English; 42 were not intervention studies; the study design of 3 did not meet criteria; the populations studies in 36 did not meet criteria; the interventions of 125 did not meet criteria; 6 did not measure the primary outcomes; 12 did not provide enough information (e.g., conference abstracts); and 2 did not satisfy risk of bias criteria. A total of 17 articles, involving 18 studies, were identified for inclusion in the systematic review (Fig. 1). The corresponding authors of all included studies were contacted to provide further information for data extraction and/or risk of bias assessment. Of the nine corresponding authors of the 17 included articles and 18 individual studies, seven authors/co-authors responded and six were able to provide some or all further information requested on a total of 16 studies (See Tables S4-17 in the Supplementary Information Document for correspondence and additional information from the authors of included papers).

3.3. Study characteristics

The included studies were characterised by both non-randomised (44.44%) and randomised (55.56%) interventions. The studies involved a total of 620 participants, the majority diagnosed with DD (91.40%). Variants of a total of seven visuo-attentional interventions covering three main types – referred to here as action video games (AVGs; $n = 5$), reading acceleration programs (RAPs; $n = 8$), and visual perceptual training (VPT; $n = 5$) – were included and compared against control treatments (38.80%), no treatment (27.70%), and comparison treatments or groups (55.50%). Of the primary reading outcomes, 66.67% of studies assessed text/word reading accuracy, 61.11% assessed text/word reading rate, 50% assessed text/word reading fluency, and 27.78% assessed reading comprehension. Although not the focus of the current review, many of the included studies also assessed non-reading outcomes, such as phonological awareness (50%), pseudoword decoding (66.67%), visuo-attentional processes (61.11%), short-term working and long-term memory (27.78%), and spelling (22.22%) (See supplementary document Table S2 for further information). Study characteristics are presented in Table 4 and include any additional information provided by study authors. Additional information collected mainly pertained to information on location of study, blinding of participants/personnel/outcome assessors, pre/post-test period, age ranges, and SMD.

Table 2
ROBINS-I Risk of Bias Assessment for Non-Randomised Trials.

Author	confounding	Selection of Participants	Classification of Intervention	Deviations from Intended interventions	Missing Data	Measurement of Outcomes	Reported Result	Overall
Das-Smaal et al., 1996	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡
Franceschini et al., 2013	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡
Franceschini et al., 2017a.2	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡
Gori et al., 2016	🟢	🟢	🟢	🟢	🟢	🟠	🟡	🟠
Judica et al., 2002	🟡	🟢	🟢	🟡	🟢	🟡	🟡	🟡
Lawton 2007	🟠	🟢	🔴	🔴	🟢	🟢	🔴	🔴
Lawton 2008	🟡	🟢	🟠	🟢	🟢	🟡	🟡	🟠
Lawton, 2011	🟠	🔴	🔴	🔴	🟢	🟠	🔴	🔴
Luniewska et al., 2018	🟡	🟢	🟢	🟢	🟢	🟡	🟡	🟡
Meng et al., 2014	🟡	🟢	🟢	🟢	🟢	🟢	🟡	🟡

Table 3
Cochrane Risk of Bias Assessment for Randomised Trials.

Author	Random Sequence Generation	Allocation Concealment	Blinding of Participants/ Personnel	Blinding of Outcome Assessment	Incomplete Outcome Data	Selective Reporting	Other Sources of Bias	**Overall**
Facoetti et al., 2003	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟢
Franceschini et al., 2017a.4	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢
Franceschini et al.,2017b	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟢
Lawton, 2004	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟢
Lawton, 2016	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🟢
Lawton et al., 2017	🔴	🟡	🔴	🟢	🟢	🔴	🟢	🟢
Lorusso et al., 2004	🔴	🟢	🟢	🟢	🟢	🟡	🟢	🟢
Lorusso et al., 2005	🔴	🟢	🟢	🟢	🟢	🟡	🟢	🟢
Lorusso et al., 2006	🔴	🟢	🟢	🟢	🟢	🟡	🟢	🟢
Lorusso et al., 2011	🔴	🟢	🟢	🟢	🟢	🟡	🟢	🟢

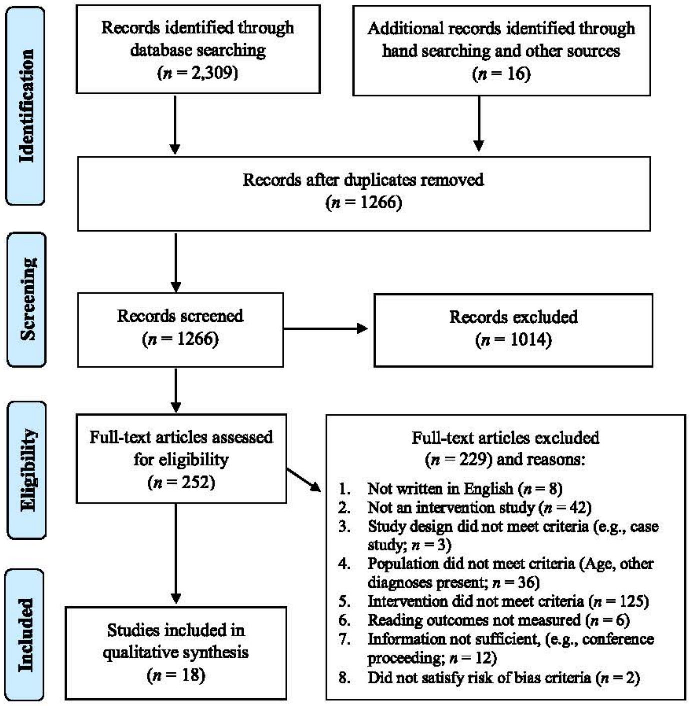

Fig. 1. PRISMA flow diagram depicting how articles were selected for review.

3.4. Results of individual studies

Information from the included studies are presented in Table 5 with any additional information that has been provided by study authors. For each study, Table 5 summarises the citation, matched group design (if relevant), intervention and group size information, duration of the interventions, pre/post-test period, and the various reading outcome measures, including SMD or estimated SMD where calculation was possible (see supplementary document Table S2 for non-reading outcome information). In line with the aims of this review, any combined outcome measures of reading were separated where possible. Individual outcomes were not able to be separated for three studies which used composite measures of reading that included word, pseudoword, and text reading tasks (Lorusso et al., 2011, 2004; Lorusso et al., 2006). Additionally, where relevant, only main group outcomes were included for studies that also compared outcome efficacy between sub-types of dyslexia. Main group outcomes were not available for one paper and so results for dyslexic subtypes have been provided (Lorusso et al., 2011). As hypothesised in the pre-specified protocol, heterogeneity of the interventions precluded meta-analysis across the included studies. Six of the 18 studies did not provide sufficient information to be included in a meta-analysis, while several more papers did not include sufficient information for every reading outcome. Further, meta-analysis within the three overarching intervention types that have been identified in the current systematic review was not considered appropriate as interventions within subtypes were still diverse, and studies of the same intervention protocol were predominately by the same groups of authors and therefore susceptible to possible non-independence (Noble et al., 2017). Therefore, it was necessary to conduct a qualitative synthesis to best capture the breadth of research on this topic.

Table 4
Characteristics of Included Studies.

#	Citation	Language	Study Design	Participants: *N*	Participants: Age M (SD); Range	Participants: Diagnostic Criteria	Intervention Details: Intervention	Intervention Details: Administration/ Location	Intervention Details: Skills Assessed (Tests Used)	Aims Concealed?: Participants	Aims Concealed?: Assessors
1	Das-Smaal et al., 1996	Dutch	NRCT	*N* = 33 with Dyslexia	9.68; 9 - 10	Reading > 2 years below age norms; 'average intelligence' Further classified into Bakker's subtypes	Multi-letter Reading Acceleration Program Vs Maths and Finger Exercises (Control)	Group; School	• Word reading accuracy, rate and fluency (Word and Flashword Tasks*) • Pseudoword decoding accuracy, rate and fluency (Word and Flashword Tasks*) • Multi-letter unit identification (Unit Detection Task*)	N/A	N
2	Facoetti et al., 2003	Italian	RCT	*N* = 24 with Dyslexia	9.84; 7 - 9	DSM-IV (reading ≥ 2SD below age norms); IQ ≥ 85 Further classified into Bakker's subtypes	VHSS Vs Standard Reading Treatment (Comparison)	Individual; Hospital	• Text Reading accuracy, rate and fluency (La verifica dell'apprendimento della lettura) • Covert visual attention orienting*	Y	Y
3	Franceschini et al., 2013	Italian	NRCT	*N* = 20 with Dyslexia	9.84 (1.43); 8 - 11	DSM-IV (reading ≥ 2SD below age norms); IQ ≥ 85	AVG Vs NAVG (Control)	Individual; Hospital	• Text reading accuracy and rate (MT) • Pseudoword decoding list accuracy and rate (DDE) • Pseudoword decoding list accuracy and rate * • Pseudoword text accuracy and rate* • Phonological awareness - syllabic blending* • Focused and distributed visual spatial attention* • Cross-modal attention*	Y	Y
4	Franceschini et al., 2017a Experiment 2	Italian	NRCT - crossover	*N* = 13 with Dyslexia	10.17 (1.87); 8 - 14	DSM-5 (reading ≥ 1.5 SD below age norms); IQ ≥ 85	'The Library Tower' Reading Acceleration Program Vs No Treatment	Individual; Rehabilitation Centre	• Text reading accuracy and rate (DDE) • Pseudoword decoding accuracy and rate (Batteria De.Co.Ne. per la lettura) • Phonological awareness - pseudoword repetition (VAUMeLF) • Navon multiple stimuli naming task*	Y	N
5	Franceschini et al., 2017a Experiment 4	Italian	RCT	*N* = 14 with Dyslexia	10.41 (1.71); 8 - 14	DSM-5 (reading ≥ 1.5 SD below age norms); IQ ≥ 85	AVG Vs NAVG (Control)	Individual; Clinical Centre	• Text reading accuracy and rate (DDE) • Pseudoword decoding accuracy and rate* • Navon task*	Y	Y
6	Franceschini et al., 2017b	English (Aus)	RCT	*N* = 28 with Dyslexia	10.10; 7.8 - 14.3	Documented diagnosis; IQ ≥ 85	AVG Vs NAVG (Control)	Individual; University	• Word reading accuracy and rate (TOWRE-2) • Pseudoword decoding accuracy and rate (TOWRE-2) • Auditory-phonological working memory - short-term memory for trigrams and phoneme blending tasks* • Focused and distributed visual spatial attention* • Visual, auditory, and visual-auditory processing* • Cross-sensory attention shifting*	Y	Y

(*continued on next page*)

Table 4 (*continued*)

#	Citation	Language	Study Design	Participants: *N*	Participants: Age M (SD); Range	Participants: Diagnostic Criteria	Intervention Details: Intervention	Intervention Details: Administration/ Location	Intervention Details: Skills Assessed (Tests Used)	Aims Concealed?: Participants	Aims Concealed?: Assessors
7	Gori et al., 2016 Experiment 3	Italian	NRCT, crossover	*N* = 11 with Dyslexia	11.02 (1.26); 9.9 - 12.9	DSM-5 (reading ≥ 2SD below age norms); IQ ≥ 85	AVG Vs NAVG (Control)	N/A	● Text reading fluency (ratio between accuracy and rate; DDE) ● Pseudoword decoding fluency* ● Phonological awareness - Pseudoword repetition (VAUMeLF) ● Coherent dot motion task* ● Illusory motion task* ● Parvocellular-ventral task*	Y	N/A
8	Judica et al., 2002	Italian	NRCT	*N* = 18 with Dyslexia	11.83 (0.63); 11 - 12	Reading accuracy and/or rate ≥ 1.65 SD below age norms on two reading tests; IQ ≥ 80	'Tachistoscopio' Reading Acceleration Program Vs No Treatment	Individual; School	● Text reading accuracy, rate and comprehension (MT) ● Word reading accuracy and rate (DDD) ● Pseudoword decoding accuracy and rate, homophonic word correction, lexical decision accuracy and rate (DDD) ● Eye movements during reading* ● Vocal reaction times during reading*	N	N
9	Lawton, 2004	English (USA)	RCT	*N* = 33 with Dyslexia	7.3 (0.5); 6.1 - 8.2	Identified using the Dyslexia Determination Test; 'normal intelligence'	'Moving to Read' DDT Vs Word Discrimination (Control) Vs No Treatment	Group; School	● Reading comprehension (GSRT) ● Computerised reading fluency test* ● Reading grade level (Dyslexia Determination Test) ● Word reading accuracy and spelling (WRAT3) ● Processing speed (WISC)	Y	Y
10	Lawton, 2008	English (USA)	NRCT	*N* = 30 15 Typically Developing 15 with Dyslexia	7.0 (0.5); 5 - 9	Identified using The Dyslexia Screener; 'normal intelligence'	'PATH to Reading' DDT	Individual; School	● Computerised reading fluency test* ● Filtered text reading rate* ● Reading fluency across treatment frequency	N	Y
11	Lawton, 2016	English (USA)	RCT	*N* = 58 with Dyslexia	7.40 (0.40); 7-8	Identified using the DESD	'PATH to Reading' DDT Vs FastForWord (Comparison) Vs Linguistic Word Building (Control)	Both Individual and Group; School	● Computerised reading fluency test* ● Reading comprehension (GORT) ● Phonological awareness – Blending words subtest(CTOPP) ● Attention (CAS) ● Sequential and nonsequential visual and auditory working memory, and delayed recall (TIPS) ● Direction discrimination*	Y	Y
12	Lawton and Shelley-Tremblay, 2017	English (USA)	RCT	*N* = 42 20 Typically Developing 22 with Dyslexia	8.5 (0.5); 7.6 – 9.7	Identified using the Dyslexia Determination Test	'PATH to Reading' DDT Vs 'Raz-Kids' Guided Reading (Comparison)	Group; School	● Computerised reading fluency test* ● Text reading comprehension (GORT-5) ● Phonological awareness – Blending word subtest (CTOPP) ● Attention – Stroop and number detection subtests(CAS)	N	Y

(continued on next page)

Table 4 (*continued*)

#	Citation	Language	Study Design	Participants: *N*	Participants: Age M (SD); Range	Participants: Diagnostic Criteria	Intervention Details: Intervention	Intervention Details: Administration/ Location	Intervention Details: Skills Assessed (Tests Used)	Aims Concealed?: Participants	Aims Concealed?: Assessors
									● Sequential and non-sequential visual and auditory working memory, and delayed recall (TIPS)		
13	Lorusso et al., 2004	Italian	RCT	*N* = 30 with Dyslexia	10.35 (1.76); 7 - 14	ICD-10 (reading ≥ 2SD below age norms); IQ > 85	Various manipulations of 'Flash Word' VHSS	Individual; Outpatient Clinic	● Text reading accuracy and rate (MT) ● Word reading accuracy and rate (DDE) ● Pseudoword decoding accuracy and rate, spelling (DDE)	Y	Y
14	Lorusso et al., 2005	Italian	RCT	*N* = 12 with Dyslexia	8 - 14	ICD-10 (reading ≥ 2SD below age norms); IQ > 85 Further classified into Bakker's subtypes	Standard Lateral 'Flash Word' VHSS Vs Random Lateral 'Flash Word' VHSS	Individual; Hospital	● Word reading accuracy and rate (DDE) ● Pseudoword decoding accuracy and rate (DDE) ● Visual spatial attention – Form resolving field*	Y	Y
15	Lorusso et al., 2006	Italian	RCT	*N* = 25 with Dyslexia	9.84 (2.19); 7 - 15	ICD-10 (reading ≥ 2SD below age norms); IQ > 85 Further classified into Bakker's subtypes	Standard Lateral 'Flash Word' VHSS Vs Standard Reading Treatment (Comparison)	Individual; Outpatient Clinic	● Text reading accuracy and rate (MT) ● Word reading accuracy and rate (DDE) ● Pseudoword decoding accuracy and rate, spelling (DDE) ● Phonological awareness* ● Working memory and memory (TEMA)	Y	Y
16	Lorusso et al., 2011	Italian	RCT	*N* = 123 with Dyslexia	10.53 (1.83); 7 - 15	ICD-10 (reading ≥ 2SD below age norms); IQ > 85 Further classified into Bakker's subtypes	Various manipulations of 'Flash Word' VHSS Vs Standard Reading Treatment (Comparison)	Individual; Outpatient Clinic	● Text reading accuracy and rate (MT) ● Word reading accuracy and rate (DDE) ● Pseudoword decoding accuracy and rate, spelling (DDE) ● Phonological awareness* ● Working memory and memory (TEMA)	Y	Y
17	Luniewska et al., 2018	Polish	NRCT	*N* = 70 with Dyslexia	11.25; 8.8 - 14	Documented diagnosis, confirmed with standardized assessment (IQ and reading tests); IQ ≥ 85	AVG Vs Phonological video game (comparison) Vs No Treatment (only completed the web-based outcome tasks)	Both Individual and Group; Research Institute	● Word reading rate and fluency (Test Dekodowania) ● Pseudoword decoding rate and fluency (Test Dekodowania) ● Phoneme deletion (Diagnoza dysleksji u uczniów kl. III szkoły podstawowej) ● Vowel replacement task ● Pseudoword repetition (Test powtarzania pseudosłów) ● Selective attention (IDS Skale Inteligencji) ● Rapid naming – objects, colours, numbers, letters (Test Szybkiego Nazywania) ● Real word recognition, sentence reading comprehension, and	N	Y

(continued on next page)

Table 4 (*continued*)

#	Citation	Language	Study Design	Participants: N	Participants: Age M (SD); Range	Participants: Diagnostic Criteria	Intervention Details: Intervention	Intervention Details: Administration/ Location	Intervention Details: Skills Assessed (Tests Used)	Aims Concealed?: Participants	Aims Concealed?: Assessors
									pseudoword decoding tasks – Web-based tasks*		
18	Meng et al., 2014	Chinese	NRCT	N = 36 18 Typically Developing 18 with Dyslexia	10.87 (0.76); 8 - 12	1.5 grade level delay in character recognition; below average reading fluency scores; typical IQ.	Texture Discrimination Vs No Treatment	N/A; University	● Text reading fluency (The Reading Fluency Test) ● Vocabulary – real character recognition (The Standardised Chinese Character Recognition Test) ● Texture discrimination task*	N/A	N/A

Note. N/A = Information was not available. **Interventions:** VHSS = Visual Hemispheric Specific Stimulation; AVG = Action Video Game; NAVG = Non-Action Video Game (Control Treatment); DDT = Direction Discrimination Training; Standard Reading Treatment refers to remediation programs commonly used by clinicians for the treatment of dyslexia that target reading sub-skills, such as phonological awareness, and teach guided reading and compensatory strategies; the Phonological Video Game trained phonological skills and did not meet criteria as an action video game; **Skills Assessed:** Bolded text = reading outcomes of interest; * = task is experimental; CAS = Cognitive Assessment Systems test of Expressive Attention; CTOPP = Comprehensive Test of Phonological Processing; DDD = Developmental Dyslexia and Dysorthography battery DDE = Batteria per la Valutazione della Dislessia e della Disortografia Evolutiva; DESD = Decoding Encoding Screener for Dyslexia; GORT = Gray Oral Reading Test; GSRT = Gray Silent Reading Test; MT = MT Reading Test (Test for speed and accuracy in reading, developed by the MT group/Prove di rapidita e correttezza nellalettura del gruppo MT; TEMA = Test di Memoria e Apprendimento; TIPS = Test of Information Processing Skills (TIPS); TOWRE-2 = Test of Word Reading Efficiency 2; VAUMeLF = Batterie per la valutazione dell'attenzione uditiva e della memoria di lavoro fonologica in età evolutiva; WISC = Wechsler Intelligence Scale for Children; WRAT3 = Wide Range Achievement Test 3.

3.4.1. *Description of RAPs*

The visually-based RAP studies used a variety of programs. These studies did not include explicit phonological training but do require children to read words and sentences (sometimes with feedback) and so cannot be said to be only reliant on visuo-attentional mechanisms. Further, the studies included only consist of those that investigated RAP interventions from a visuo-attentional perspective (thus meeting inclusion criteria). The program used by Das-Smaal et al. (1996) required participants to view a briefly presented multi-letter unit then identify whether it was present in an ensuing word. Presentation time was decreased with correct responses (program adapted from Frederiksen et al., 1985). Franceschini et al. (2017a) developed 'The Library Tower', an open access, sentence level program in the Italian language that required participants to read the sentence silently then answer a corresponding multiple-choice question, with presentation duration decreased with correct responses (for further information about the program 'The Library Tower', see Supplementary Information from Franceschini et al., 2017a). A commercially available program 'Tachistoscopio' was used by Judica, et al. (2002) and required participants to read single words then type the presented word, with presentation duration and word difficulty and length adjusted (program developed by Morchio et al., 1989). Visual Hemispheric Specific Stimulation (VHSS) was investigated by five of the included studies, (Facoetti et al., 2003; Lorusso et al., 2011, 2004; Lorusso et al., 2006, 2005), with most using a program called 'Flash Word' (developed by Masutto and Fabbro, 1995). Traditional VHSS presents words in the peripheral visual field and requires participants to read the word aloud, with presentation time, word length and complexity adjusted. Some VHSS variations used in the included studies manipulated whether words were presented centrally or peripherally, and whether presentation time was reduced or fixed. In addition to more recent evidence that VHSS induces visuo-attentional orienting via peripheral processing, VHSS is conventionally based on Bakkers theory of an imbalance in the hemispheric contributions to reading (Bakker et al., 1990).

3.4.2. *Description of VPT*

Visual perceptual training studies comprised two treatment programs. Four studies, conducted by the program designer (Lawton, 2004), investigated direction discrimination training (DDT) using the commercially available program 'PATH to reading' and its precursor, 'Moving to Read'. DDT uses a figure/ground motion discrimination paradigm and required the participant to view moving stripes (sinusoidal gratings) embedded at the centre of a striped background and discriminate the direction of movement. Contrast thresholds and spatial frequencies of the centre and background sinusoidal gratings were manipulated in all studies to increase complexity, and one study also manipulated the sinusoidal grating movement speed (See Fig. 1 from Lawton and Shelley-Tremblay, 2017). DDT was designed to address visual timing deficits found in those with DD by maximally targeting the dorsal 'where' pathway and its M pathway projections. The high motion and low contrast components at low spatial frequency maximally activated M cells, while higher spatial frequency and higher levels of contrast were used in the program to increase parvocellular (P) type activity and task complexity. One study used texture discrimination training (TDT). TDT comprised a texture display made of high contrast horizontal line segments with either a randomly rotated letter "T" or "L" as the central fixation point (See Fig. 1 from Meng et al., 2014). A briefly presented target array, in either the upper left or right visual field, was produced by rotating three horizontally or vertically adjacent bars in the texture stimuli to form either a horizontal or vertical form. The participant was required to identify both the fixation letter and direction of the target array. A 2-down 1-up staircase procedure was used to adjust the stimulus-to-mask onset asynchrony and determine participants' task threshold. TDT aimed to improve visual perceptual performance by training temporal processing speed, as well

Table 5
Main Results of Included Studies.

#	Citation	Covariates Matched between Groups	Intervention Group *N* and Description	Intervention Duration	Pre/Post Treatment Test Period	Reading Outcomes (*p*, SMD)
1	Das-Smaal et al., 1996	Age, IQ, Reading	Treatment Group $n = 17$ with DD Multiletter Reading Acceleration Program Active Control Group $n = 16$ with DD Computerized maths and motor finger exercises	30 minute sessions, twice a week for 8 weeks (16 sessions). Total = 8 hours	Within 2 weeks of treatment	Word Reading Accuracy – Both groups improved significantly following treatment, $p < .05$ Word Reading Rate – Neither group improved significantly following treatment, $p < .01$ Word Reading Fluency – The treatment group improved significantly more than controls following treatment, $p < .05$
2	Facoetti et al., 2003	Age, IQ, Reading, Attention	Treatment Group $n = 12$ with DD Standard lateral presentation VHSS Comparison Group $n = 12$ with DD Standard Reading Treatment	45 minute sessions, conducted twice weekly for 4 months (32 sessions). Total = 24 hours	2 - 7 days before and following treatment	Text Reading Accuracy – Only the VHSS group improved significantly following treatment, $p < .02$ Text Reading Rate - Only the VHSS group improved significantly following treatment, $p < .0001$
3	Franceschini et al., 2013	Age, Reading, Phonological Ability	Treatment Group $n = 10$ with DD AVG Active Control Group $n = 10$ with DD NAVG	80 minute sessions, conducted each weekday for 2 weeks (9 sessions). Total = 12 hours	3-5 days before treatment and 1-3 days following treatment	Text Reading Rate – only the AVG group improved significantly following treatment, $p = .02$, SMD = 0.67 Text Reading Accuracy – analyses not provided Text Reading Fluency (ratio between accuracy and rate) – only the AVG group improved significantly following treatment, $p = .03$, SMD = 0.99
4	Franceschini et al., 2017a Experiment 2	Not Applicable	$N = 13$ with DD No Treatment followed by the 'The Library Tower' Reading Acceleration Program	No treatment phase: 2 to 3 week period of no treatment. The Library Tower treatment phase: 40 minute sessions, conducted most days for 2 or 3 weeks (10 sessions). Total = 6 hours, 40 minutes	1 - 3 days before and after each treatment phase	Text Reading Accuracy – Participants did not significantly improve following either treatment phase, $p = .41$, SMD = 0.55 Text Reading Rate – Participants improved significantly only following RAP treatment, $p = .04$, SMD = 0.29 Two months following treatment, participant's had maintained performances for reading accuracy, $p = .16$, and reading rate, $p = .44$.
5	Franceschini et al., 2017a Experiment 4	Reading; Phonological Ability Age differed between groups, $p = .001$	Treatment Group $n = 7$ with DD AVG Active Control Group $n = 7$ with DD NAVG	80 minute sessions, conducted each weekday for 2 weeks (9 sessions). Total = 12 hours	3-5 days before treatment and 1-3 days following treatment	Text Reading Accuracy – Neither the AVG nor NAVG groups improved significantly following treatment, $p > .05$, SMD = 0.81 Text Reading Rate - Only the AVG group improved significantly following training, $p = .032$, SMD = 1.21
6	Franceschini et al., 2017b	Age, Reading	Treatment Group $n = 16$ with DD AVG Active Control Group $n = 12$ with DD NAVG	80 minute sessions, conducted each weekday for 2 weeks (9 sessions). Total = 12 hours	3-5 days before treatment and 1-3 days following treatment	Word Reading Accuracy - Neither the AVG nor NAVG groups improved significantly following treatment, $p > .05$ Word Reading Rate – Only the AVG group improved significantly following training, $p = .024$, SMD = 0.86
7	Gori et al., 2016 Experiment 3	Not applicable	$N = 11$ with DD NAVG followed by AVG	For each treatment program: 80 minute sessions, conducted each weekday for 2 weeks (9 sessions). Total = 12 hours each	3-5 days before each treatment and 1-3 days following each treatment	Text Reading Fluency (mean of accuracy and rate) – Participants improved significantly only following AVG treatment, $p = .013$, eSMD = 0.80
8	Judica et al., 2002	Age, IQ, Reading	Treatment Group $n = 9$ with DD 'Tachistoscopio' Reading Acceleration Program Control Group $n = 9$ with DD No treatment provided	1 hour sessions, conducted twice weekly for 5 months (35 sessions). Total = 35 hours	Within 1 month before treatments and within 2 weeks following treatment	Text Reading Accuracy – Only the treatment group improved significantly following the treatment period, $p < .05$, SMD = 0.88 Text Reading Rate – Neither group improved, the control group performed significantly worse following the treatment period, $p < .05$, SMD = 0.45

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Table 5 (*continued*)

#	Citation	Covariates Matched between Groups	Intervention Group *N* and Description	Intervention Duration	Pre/Post Treatment Test Period	Reading Outcomes (*p*, SMD)
						Text Reading Comprehension – Both groups performed significantly worse following the treatment period, $p < .05$ Word Reading Accuracy – Only the treatment group improved significantly following treatment, $p < .05$, SMD = 0.64 Word Reading Rate – Only the treatment group improved significantly following treatment, $p < .05$, SMD = 0.38
9	Lawton, 2004	Reading	Treatment Group $n = 18$ with DD 'Moving to Read' DDT Active Control Group $n = 9$ with DD Word Discrimination Game Control Group $n = 6$ with DD No Treatment	5-10 minute sessions, conducted twice weekly for 15 weeks (30 sessions). Total = 2.5 to 5 hours	Within 1 week of treatment	Reading Comprehension - The DDT group improved significantly more than the other groups following training, $p = .02$ ● DDT Vs. Word Game, SMD = 1.40 ● DDT Vs No Treatment, SMD = 1.00 Text Reading Fluency – The DDT group improved significantly more than the other groups following training, $p = .0008$ ● DDT Vs. Word Game, SMD = 1.80 ● DDT Vs. No Treatment, SMD = 1.98 Reading Grade Level - The DDT group improved significantly more than the other groups following training, $p = .006$ ● DDT Vs. Word Game, SMD = 1.10 ● DDT Vs. No Treatment, SMD = 1.30 Word Reading Accuracy - The DDT group improved significantly more than the other groups following training, $p = .016$ ● DDT Vs. Word Game, SMD = 0.50 ● DDT Vs. No Treatment, SMD = 0.90
10	Lawton, 2008	Age, Grade Level	Treatment Group $n = 15$ with DD 'PATH to Reading' DDT of between two and six replications Treatment Comparison Group $n = 15$ TD 'PATH to Reading' DDT of between two and six replications	10-15 minute sessions, conducted weekly. For between 2 and 6 replications of treatment. Total = 1 to 3 hours	Within 1 week of treatment	Text Reading Fluency - Both groups improved significantly following treatment, $p < .01$ Text Reading Fluency improved significantly more as frequency of training was increased, $p < .001$
11	Lawton, 2016	Age, Reading, Attention, Working Memory	Treatment Group $n = 26$ with DD 'PATH to Reading' DDT Comparison Group $n = 6$ with DD 'FastForWord' Auditory Timing Treatment Active Control Group $n = 26$ with DD Linguistic Word Building	DDT: 15-30 min sessions, conducted 3 days per week, for 20 weeks (60 sessions). Total = 20 to 30 hours FastForWord: 30 min sessions, conducted 5 days per week for 20 weeks (100 sessions). Total = 50 hours	Within 1 week of treatment	Reading Fluency – The DDT group improved significantly more than the control group, $p = .0004$, and FastForWord group following training, $p < .001$ ● PATH Vs Word Game, estimated SMD = 0.83 ● PATH Vs FastForWord, estimated SMD = 1.71 Reading Comprehension - The DDT group improved significantly more than the control group, $p = .046$, but not FastForWord group, which improved significantly more following treatment, $p = 0.0011$ ● PATH Vs Word Game, estimated SMD = 0.56 ● PATH Vs FastForWord, estimated SMD = -1.63
12	Lawton and Shelley-Tremblay, 2017	Age, Phonological Ability, Attention, Working Memory	Treatment Group $n = 12$ with DD 'PATH to Reading' DDT	DDT = 15 - 20 minute sessions, three times a week for 12 weeks (36 sessions). Total = 9 - 12 hours	Within 1 week of treatment	Reading fluency - Both DDT groups improved significantly more that the Raz-Kids groups following treatment, $p = .006$

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Table 5 (*continued*)

#	Citation	Covariates Matched between Groups	Intervention Group N and Description	Intervention Duration	Pre/Post Treatment Test Period	Reading Outcomes (p, SMD)
		Reading was matched between the DD and TD groups respectively	Treatment Group $n = 9$ TD 'PATH to Reading' DDT Comparison Group $n = 10$ with DD 'Raz-Kids' Guided Reading Comparison Group $n = 11$ TD 'Raz-Kids' Guided Reading	RazKids = 30 minute sessions, three times a week for 12 weeks (36 sessions). Total = 18 hours		• TD PATH Vs TD Raz Kids, estimated SMD = 1.29 • DD PATH Vs DD Raz Kids, estimated SMD = 1.23 • DD PATH Vs TD PATH, estimated SMD = -1.27 Reading Comprehension - Both the DDT groups improved significantly more that the Raz-Kids groups following treatment, $p = .001$ • TD PATH Vs TD Raz Kids, estimated SMD = 1.65 • DD PATH Vs DD Raz Kids, estimated SMD = 1.57 • DD PATH Vs TD PATH, estimated SMD = -1.62
13	Lorusso et al., 2004	Age, IQ, Reading, Sex	Treatment Group $n = 9$ with DD Standard Lateral (SL) Presentation 'Flash Word' VHSS Treatment Group $n = 7$ with DD Random Lateral (RL) Presentation 'Flash Word' VHSS Treatment Group $n = 8$ with DD Central (C) Presentation 'Flash Word' VHSS Treatment Group $n = 6$ with DD Central Fixed-Time (CFT) 'Flash Word' VHSS	45 minute sessions, conducted twice a week over a 4 month period (32 sessions). Total = 24 hours	4-5 days before and following treatment	Global Reading Accuracy (a composite of text, word and pseudoword reading accuracy tasks) – All groups improved significantly following treatment, $p < .001$ • SL Vs RL, SMD = 0.01 • SL Vs C, SMD = -0.17 • SL Vs CFT, SMD = -0.32 • RL Vs C, SMD = -0.30 • RL Vs CFT, SMD = -0.45 • C Vs CFT, SMD = -0.15 Global Reading Rate (a composite of text, word and pseudoword reading rate tasks) – All groups improved significantly following treatment, $p < .001$ • SL Vs RL, SMD = -0.46 • SL Vs C, SMD = -0.12 • SL Vs CFT, SMD = -0.59 • RL Vs C, SMD = 0.34 • RL Vs CFT, SMD = -0.13 • C Vs CFT, SMD = -0.47
14	Lorusso et al., 2005	Age, Reading	Treatment Group $n = 6$ with DD Standard Lateral Presentation 'Flash Word' VHSS Treatment Group $n = 6$ with DD Random Lateral Presentation 'Flash Word' VHSS	45 minute sessions, conducted twice a week over a 4 month period (32 sessions). Total = 24 hours	Immediately before and following treatment	Word Reading Accuracy – Both groups improved significantly following treatment, $p = .019$ Word Reading Rate – Both groups improved significantly following treatment, $p = .023$
15	Lorusso et al., 2006	Age, IQ, Reading, Sex	Treatment Group $n = 14$ with DD Standard Lateral Presentation 'Flash Word' VHSS Comparison Group $n = 11$ DD Standard Reading Treatment	45 minute sessions, conducted twice a week over a 4 month period (32 sessions). Total = 24 hours	Immediately before and following treatment	Global Reading Accuracy (a composite of text, word and pseudoword reading accuracy tasks) – The VHSS Group improved significantly more following treatment, $p < .001$, SMD = 1.32 Global Reading Rate (a composite of text, word and pseudoword reading rate tasks) – All groups improved significantly following treatment, $p = .001$, SMD = -0.04
16	Lorusso et al., 2011	Age, IQ, Reading, Sex	Treatment Group $n = 33$ with DD (5 L-types, 15 P-types, and 13 M-types) Standard Lateral (SL) Presentation 'Flash Word' VHSS Treatment Group $n = 22$ with DD (5 L-types, 4 P-types, and 13 M-types) Random Lateral (RL)	45 minute sessions, conducted twice a week over a 4 month period (32 sessions). Total = 24 hours	Immediately before and following treatment	Global Reading Accuracy (a composite of text, word and pseudoword reading accuracy tasks) For the P-type and L-type dyslexics, the SL VHSS group improved significantly more than the CFT and RevL VHSS groups following treatment, but did not differ significantly in improvement from the other groups. • SL Vs Phon, $p = 0.11$, estimated SMD = 0.77 • RL Vs Phon, $p = 0.35$, estimated SMD = 0.48 • C Vs Phon, $p = 0.23$, estimated SMD = 0.59 • CFT Vs Phon, $p = 0.49$, estimated SMD = -0.34

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Table 5 (*continued*)

#	Citation	Covariates Matched between Groups	Intervention Group *N* and Description	Intervention Duration	Pre/Post Treatment Test Period	Reading Outcomes (*p*, SMD)
			Presentation 'Flash Word' VHSS Treatment Group $n = 18$ with DD (2 L-types, 5 P-types, and 11 M-types) Central Presentation (C) 'Flash Word' VHSS Treatment Group $n = 15$ with DD (1 L-types, 7 P-types, and 7 M-types) Central, Fixed-Time (CFT) 'Flash Word' VHSS Treatment Group $n = 9$ with DD (2 L-type and 7 P-type only) Reversed Lateral Presentation (RevL) 'Flash Word' VHSS Treatment Group $n = 13$ (13 M-types) Right Hemisphere Lateral Presentation (RH) 'Flash Word' VHSS Comparison Group $n = 13$ with DD (3 L-types, 3 P-types, and 7 M-types) Standard Reading Treatment (SRT)			● RevL Vs Phon, $p = 0.58$, estimated SMD = -0.27 For the M-type dyslexics, groups did not differ significantly in improvement following treatment, *ps* > .10 ● SL Vs SRT, estimated SMD = 0.62 ● RL Vs SRT, estimated SMD = 0.56 ● C Vs SRT, estimated SMD = 0.53 ● CFT Vs SRT, estimated SMD = 0.73 ● RH Vs SRT, estimated SMD = 0.67 Global Reading Rate (a composite of text, word and pseudoword reading rate tasks) For the P-type and L-type dyslexics, groups did not differ significantly in improvement following treatment, *ps* > .10 ● SL Vs SRT, estimated SMD = -0.24 ● RL Vs SRT, estimated SMD = -0.34 ● C Vs SRT, estimated SMD = -0.58 ● CFT Vs SRT, estimated SMD = 0.61 ● RevL Vs SRT, estimated SMD = 0.02 For the M-type dyslexics, groups did not differ significantly in improvement following treatment, *ps* > .10 ● SL Vs SRT, estimated SMD = -0.72 ● RL Vs SRT, estimated SMD = -0.52 ● C Vs SRT, estimated SMD = -0.44 ● CFT Vs SRT, estimated SMD = -0.18 ● RH Vs SRT, estimated SMD = -0.52
17	Luniewska et al., 2018	Age, IQ, Reading	Treatment Group $n = 27$ with DD AVG Comparison Group $n = 27$ with DD Phonological Video Game Control Group $n = 16$ with DD No Treatment	50 minutes sessions, completed across 22-36 days (16 sessions). Total = 13.3 hours	AVG and PNAVG groups: 0-7 days (M = 1.5) before treatment and 1 - 18 days (M = 4.8) following treatment Control group: 16-60 days apart (M = 38.3)	Outcomes compared between AVG and PNAVG groups: Word Reading Rate – Both the AVG and PNAVG groups improved following training, $p = .001$, SMD = 0.27 Word Reading Fluency – Both the AVG and PNAVG groups improved following training, $p = .001$, SMD = 0.18 Outcomes compared between AVG, PNAVG, and Control groups: Sentence Reading Comprehension – All groups improved significantly over time, $p = .049$, ● AVG Vs PNAVG, SMD = 0.08 ● AVG Vs Control, SMD = -0.03 Groups were re-assessed one month later. Again, all groups improved significantly with time, $p < .001$

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Table 5 (*continued*)

#	Citation	Covariates Matched between Groups	Intervention Group *N* and Description	Intervention Duration	Pre/Post Treatment Test Period	Reading Outcomes (*p*, SMD)
18	Meng et al., 2014	Age, IQ, Reading, Texture Discrimination were matched within the DD and TD groups respectively	Treatment Group *n* = 9 with DD Texture Discrimination Training Treatment Group *n* = 9 TD Texture Discrimination Training Control Group *n* = 9 with DD No treatment Control Group *n* = 9 TD No treatment	Treatment groups: 50 minute sessions, completed within 4 weeks (10 sessions). Total = 8.3 hours	N/A	Text Reading Fluency - Only the dyslexic treatment group improved significantly following the treatment period, $p < .05$ The dyslexic treatment group maintained improvement at a 2 month follow up assessment, $p > .1$.

Note. VHSS = Visual Hemispheric Specific Stimulation; AVG = Action Video Game; NAVG = Non-Action Video Game (Control Treatment); DDT = Direction Discrimination Training; TD = Typically Developing; DD = Developmental Dyslexia; Standard Reading Treatment refers to remediation programs commonly used by clinicians for the treatment of dyslexia that target reading sub-skills, such as phonological awareness, and teach guided reading and compensatory strategies; The Phonological Video Game training phonological skills and did not meet action video game criteria; SMD = Standard Mean Difference of change (also referred to as Cohen's d). Where an experimental treatment is compared to a control or comparison treatment, a positive SMD is in favour of the visuo-attention intervention, in studies with more than 2 groups, the SMD is in favour of the first intervention listed. Small = 0.2, medium = 0.5 and large = 0.8 effect sizes respectively.

as visual span and spatial attention via high peripheral processing demands.

3.4.3. Description of AVGs

All investigations of AVGs used the same mini-games from the commercially available program 'Raymans Raving Rabbids' (see Ubisoft, 2006). Selected mini-games met the following AVG criteria, 1) speed; 2) high levels of cognitive, perceptual and motor load; 3) divided attention; and 4) high levels of peripheral processing (Green and Bavelier, 2012). Examples of the mini-games include first-person shooter style games where Rayman must shoot rabbid bunnies with a plunger gun in order to avoid being touched by the bunnies that appear unpredictably from any direction, go-no-go style games in which rayman must sneak up a rabbid bunny while attending to fast visual cues, and labyrinth games where Rayman must navigate as quickly as possible without touching the sides of the maze (for a full list and description of mini-games used, see Supplementary Information from Franceschini et al., 2013). Four of the studies compared the AVG to a non-AVG (active control treatment using video games that did not meet AVG criteria) using 'Raymans Raving Rabbids' mini-games that did not satisfy AVG criteria, while the fifth study compared the AVG to an experimental phonological video game that trained phonological processing and did not meet criteria as an AVG, and a no treatment group.

4. Discussion

Out of 2288 records, 18 studies met the inclusion and risk of bias criteria for this review. The studies, while written in English, investigated reading outcomes across five languages, and included a heterogeneity of intervention durations, intervention intensity, comparison treatment groups and control groups, and reading outcomes. Quality of the included studies was generally fair, with non-randomised studies all assigned an overall moderate risk of bias (i.e., sound for a non-randomised study, but not comparable to a well-performed randomized trial) and randomised studies all assigned an overall low risk of bias. Only three studies evaluated the efficacy of visuo-attentional interventions of the reading outcomes of typically developing children, three studies included short-term follow-up assessments, and only one study investigated whether increasing intervention resulted in greater reading gains. Overall, the studies fell into three categories, VPT (n = 5), RAPs (n = 8), and AVGs (n = 5), and so have been summarised within each of the three groups.

4.1. Visual perceptual training (VPT)

Five of the included studies investigated the effectiveness of visual perceptual interventions for reading outcomes in a total of 199 children, of which 146 were dyslexic and 53 were typically developing (Lawton, 2004, 2008, 2016; Lawton and Shelley-Tremblay, 2017; Meng et al., 2014). These intervention stimuli each target low-level visuo-attention mechanisms and do not include any phonological, orthographic or reading involvement. Four of the studies, all by the same author, investigated DDT (Lawton, 2004, 2008, 2016; Lawton and Shelley-Tremblay, 2017), while the fifth study investigated the efficacy of TDT (Meng et al., 2014). Of the included visual perceptual training studies, two included established comparison treatments (Raz-Kids Guided Reading, FastForWord), two included active control treatments, two compared the intervention to a 'no treatment' group, and one study compared the target intervention between typically developing and DD children.

4.1.1. VPT results

All five studies assessed reading fluency outcomes, with all reporting significant improvements in fluency as compared to established comparison treatments, and control groups. Effect sizes were only available for three of the studies and demonstrated large effect sizes in favour of DDT (Lawton, 2004, 2016; Lawton and Shelley-Tremblay, 2017). Typical and DD participants were shown to benefit similarly from DDT (Lawton, 2008; Lawton and Shelley-Tremblay, 2017); however, Meng et al. (2014) found that only dyslexic, not typically developing, participants improved following TDT. Further, Meng et al. (2014) found that the dyslexic group had maintained their gains in reading fluency at a two-month follow-up, while Lawton (2008) demonstrated that increasing intervention duration and intensity improved reading fluency outcomes significantly more.

Three of the DDT studies assessed reading comprehension outcomes, demonstrating that DDT improved comprehension in both TD and DD children significantly more than a guided reading comparison treatment ('Raz-Kids'; Lawton and Shelley-Tremblay, 2017), and improved comprehension in those with DD significantly more than control groups but not 'FastForWord' an auditory timing comparison treatment which improved comprehension more (Lawton, 2004,2016).

No visual perceptual training study measured reading rate outcomes and only one of the included studies assessed reading accuracy (word level), demonstrating that DDT improved accuracy significantly more than control groups, with medium to large effect sizes found respectively (Lawton, 2004). One study assessed reading grade level outcomes following intervention and found the DDT group improved significantly more than control groups (Lawton, 2004). Large effect sizes in favour of DDT were found.

Together, results indicate that visual perceptual training is efficacious in improving reading comprehension and fluency in children with DD and may also be beneficial to typically developing children. Further studies assessing reading rate and accuracy would help elucidate the benefit of visual perceptual training programs on other reading outcomes. Although only tentative conclusions can be drawn regarding the impact of orthography on intervention efficacy due to the small number of studies, results suggest that children from both a deep alphabetic (English) and deep logographic orthography (Chinese) show similar benefits to reading fluency.

4.2. *Reading acceleration programs (RAPs)*

Eight of the included studies investigated the effect of interventions of computerized adaptive, rapid presentation of letter units, words or sentences, in a total of 278 dyslexic children (Das-Smaal et al., 1996; Facoetti et al., 2003; Franceschini et al., 2017a; Judica et al., 2002; Lorusso et al., 2011, 2004; Lorusso et al., 2006, 2005). What is of particular interest is that the list of included studies does not constitute all studies of RAPs but comprises the studies that have investigated these interventions from a visuo-attentional perspective and therefore have met the reviews' search terms and inclusion criteria. RAPs are argued to load working memory, rapid visual processes, attentional factors, and executive functions (Horowitz-Kraus et al., 2014), but do not include explicit phonological or orthographic training. While this group of interventions cannot be considered purely visuo-attentionally-based like the other groups of interventions included in this review, all of the included RAP studies discuss how the resulting reading improvements are mediated by improvements to visuo-attentional processing, more specifically, automatization of visual perceptual and attentional processing (Das-Smaal et al., 1996), global visual processing (Franceschini et al., 2017a; Judica et al., 2002), and rapid endogenous visuo-spatial orienting and inhibitory-controlled attentional focus (Facoetti et al., 2003; Lorusso et al., 2011, 2004; Lorusso et al., 2006, 2005). Three studies compared RAPs to a standard reading treatment (remediation programs commonly used by clinicians for the treatment of dyslexia that target reading sub-skills, such as phonological awareness, and teach guided reading and compensatory strategies), two compared various manipulations of RAPs to elucidate the processes which underpin treatment, two compared RAPs to a 'no treatment' control group, and one compared RAP to an active control treatment.

Variability in methodology between the RAP studies (i.e., whether the intervention was letter unit/word/sentence-based, comparison groups included, treatment duration) made synthesising the results particularly challenging, so results will be discussed based on outcomes.

4.2.1. *RAPs results*

All RAP studies assessed either word or text reading rate outcomes, and one study assessed both word-level and text-level reading rate. Results show that RAPs significantly improved reading rate in seven of the nine reading rate outcomes measured, more than or equal to comparison treatments, or more than control groups. RAPs improved reading rate more than a standard reading treatment in one study (Facoetti et al., 2003) and comparably to standard reading treatments in two other studies (Lorusso et al., 2011, 2006). Various manipulations of VHSS did not significantly impact on treatment efficacy with all manipulations resulting in improved reading rate (Lorusso et al., 2011, 2004; Lorusso et al., 2005) In contrast, results comparing RAPs to control groups were more variable. Franceschini et al. (2017a) found RAPs improved text reading rate significantly compared to no treatment, Judica et al. (2002) found that RAP only improved word reading rate, not text reading rate, as compared to no treatment, while Das-Smaal et al. (1996) found that RAP did not improve word reading rate outcomes. The five studies for which reading rate outcome effect sizes were available reported small to moderate effect sizes in favour of RAPs in comparison to control groups. Effect sizes were available for two of the three studies comparing RAPs to a comparison treatment option (Standard Reading Treatment; Lorusso et al., 2011, 2006). In both studies, each intervention had significantly improved reading rate outcomes comparably, and effect sizes ranged from negligible to moderate, with some (non-significantly) in favour of RAPs and others in favour of the comparison treatment.

All RAP studies assessed reading accuracy outcomes. Results show that RAPs significantly improved reading accuracy in seven of the nine accuracy outcomes measured, more than or equal to comparison treatments, or more than control groups. RAPs improved reading accuracy more than a Standard Reading Treatment in two studies (Facoetti et al., 2003; Lorusso et al., 2006), and improved comparably to a Standard Reading Treatment in another study (Lorusso et al., 2011). All types of VHSS improved reading accuracy (Lorusso et al., 2004, 2005), although type of VHSS affected the treatment efficacy (Lorusso et al., 2011). As compared to control groups, Judica et al. (2002) found RAP improved reading accuracy at both the word and text level as compared to no treatment, while the other two studies found that RAPs did not improve accuracy more than control (Das-Smaal et al., 1996) or did not improve significantly following treatment (Franceschini et al., 2017a). Studies for which effect sizes for reading accuracy outcomes were available reported moderate to large effect sizes in favour of RAPs in comparison to control groups, and mostly moderate to large effect sizes in favour of RAPs as related to established comparison treatments, although two manipulations of VHSS were (non-significantly) not as efficacious as the Standard Reading Treatment, with small effects sizes found.

Only the study by Das-Smaal et al. (1996) assessed reading fluency as an outcome, demonstrating a significant improvement only following RAP as compared to a control group. One study assessed reading comprehension outcomes, finding no improvement following treatment (Judica et al., 2002).

Together, the results are generally favourable for RAPs in improving the reading accuracy and rate of children with DD, although much more evidence comparing RAPs to both established comparison treatments as well as control interventions are necessary. Nevertheless, results from Franceschini et al. (2017a) provides initial evidence that performance following training is maintained two-months following treatment. More studies that assess reading fluency and comprehension outcomes are also warranted.

No conclusions regarding the impact of types and level of orthography on RAP efficacy for reading can be surmised as all eight studies were conducted in shallow orthographies (Italian and Dutch), highlighting a need for future studies to investigate RAPs in deep orthographies. Nonetheless, all eight studies concluded that RAPs are beneficial in improving aspects of reading. Authors concluded that RAPs work by improving rapid visual processing, leaving neural resources available for more global extraction of semantic visual information (Das-Smaal et al., 1996; Franceschini et al., 2017a; Judica et al., 2002; Lorusso et al., 2011, 2006; Lorusso et al., 2005), spatial attention (Facoetti et al., 2003; Lorusso et al., 2006, 2005), automatization (Das-Smaal et al., 1996; Lorusso et al., 2011, 2004; Lorusso et al., 2006), but also via non visuo-attentional mechanisms, including improvements to visual and auditory working memory and memory retrieval processes (Lorusso et al., 2004), appropriate use of reading strategies (Lorusso et al., 2011, 2004; Lorusso et al., 2006), and specific effects of hemispheric stimulation (Lorusso et al., 2011, 2006). Thus, while it is clear that visuo-attentional processes clearly underpin the RAPs, the relative importance of visuo-attention remains unclear.

4.3. Action video games (AVGs)

Five studies investigated the efficacy of AVGs on the reading skills of a total of 143 dyslexic children (Franceschini et al., 2017a, 2013; Franceschini et al., 2017b; Gori et al., 2016; Luniewska et al., 2018). AVGs load both temporal and spatial visuo-attention (Green and Bavelier, 2012), and have been shown to result in generalised visuo-attentional improvements beyond the trained task (Green and Bavelier, 2003; Li et al., 2009; West et al., 2008), enlarging capacity and spatial distribution of visuo-attention, and improving rapid discrimination of sequential visual stimuli and visual motion sensitivity (Green and Bavelier, 2003; Pavan et al., 2016). The AVG used across the studies also do not require or explicitly train any phonological, orthographic or reading processes in order to play the games, and so any improvements to reading outcomes can only be attributed to attentional enhancement. Additionally, children typically enjoy playing video games, and so AVGs could provide a treatment option that not only does not feel like an intervention but is also highly engaging and intrinsically motivating for children.

4.3.1. AVG results

Results show that as compared to a control group who played non-AVGs (video games that do not meet criteria as 'action-based'), only AVGs significantly improved reading rate, with moderate-to-large effect sizes found (Franceschini et al., 2017a, 2013; Franceschini et al., 2017b). The AVG also performed comparably to a phonological video game comparison treatment that trained phonological skills and did not meet AVG criteria, with both treatments improving reading rate significantly (Luniewska et al., 2018). Inspection of the SMD between the AVG and phonological video game interventions showed that the small effect size, although non-significant, was in favour of the AVG.

Both studies that assessed reading accuracy outcomes found that the AVG did not improve accuracy more than the non-AVG control group, although the one study for which a SMD was available found a large effect size between the groups (Franceschini et al., 2017a, b).

Three AVG studies measured reading fluency outcomes. Reading fluency only improved significantly for the AVG treatment and not the non-AVG control group, with large effect sizes found in the two studies (Franceschini et al., 2013; Gori et al., 2016). In contrast, Luniewska et al. (2018) found that reading fluency was improved by both AVG and the phonological video game comparison treatment options, although the small effect size was in favour (non-significantly) of AVG treatment.

Only Luniewska et al. (2018) assessed reading comprehension outcomes following AVG, compared with a phonological video game, and a no treatment control group. Results show that all groups improved over the treatment period, and also at a one-month follow-up assessment, suggesting that neither AVG nor phonological video game promoted reading comprehension any more than age development alone. Effect sizes between the three groups were negligible.

Taken together these results suggest that AVGs are efficacious in improving reading rate and fluency, but may not benefit reading accuracy or comprehension, although more studies are needed to establish interpretations. Interestingly, while most studies concluded that AVGs are beneficial in improving aspects of reading, Luniewska et al. (2018) concluded that AVG and phonological video games do not improve reading more than 'no treatment', because the groups performed comparably across web-based outcome measures (reading comprehension, real word recognition, pseudoword decoding). Yet, there are other plausible explanations. Standardised reading fluency and rates measures were only assessed in the two treatment groups, while an experimental web-based reading comprehension measure (as part of a larger battery) was used to assess and compare all three groups and was overseen by each child's parent (Luniewska et al., 2018). Thus, different reading skills were assessed and compared between the groups, and the reliability or testing conditions of the experimental web-based task is not clear. Furthermore, reading rate and fluency outcomes improved in dyslexic children across AVG studies, regardless of shallow (Italian) or deep (English & Polish) orthography.

4.4. General limitations and future directions

There were several frequent and concerning limitations to this review. Sample size is a common limitation across the three types of visuo-attentional interventions and thus impacts on the strength of the conclusions that can be drawn by this review. Most studies did not provide sufficient information in their original paper to permit adequate appraisal of some risk of bias domains. Hence all included study researchers were contacted to provide further information as well as information pertaining to study methodology and outcomes. Most non-randomised studies were assigned a moderate overall risk of bias (Sterne et al., 2016), often due to cautious interpretation of the 'reported result' domain, following the lacok of a pre-specified protocol. Randomised studies were largely assigned low risk of bias to most outcomes and low risk of bias overall, although reporting of randomisation and allocation concealment methods was almost always insufficient. Future non-randominsed studies need to improve the reporting of whether confounding domains were controlled for before the study, and how measurement of outcomes were protected from bias, while future randomised studies should improve reporting of random sequence generation and allocation concealment methods. Future studies should also report sufficient information to facilitate quality assessment and should consider pre-registering their study to reduce potential bias in the reporting of results and bias towards only publishing siginificant results. Very few studies provided SMD or other measures of effect size in their origial article. Many of the included studies were conducted by the same author or groups of authors, inflating the potential for non-independence. As only published studies were included in the current review, the presence of publication bias is not clear. Future studies should also consider using standardised reading measures over experimental measures to improve comparisons across studies.

A meta-analysis was not considered appropriate for several reasons. Six of the included papers did not provide sufficient information to be included in a meta-analysis, and others did not provide sufficient information for all primary reading outcomes included. Therefore the number of papers would be reduced significantly in terms of quantitative information for any meta-analysis, and thus the breadth of research that has been conducted in this area would not be captured. The heterogeneity of the interventions assessed (including within our subgroups), treatment durations within same/similar interventions (e.g., 1–30 h within studies assessing direction discrimination training), and reading outcomes measured are also substantial, representing serious limitations that would negatively affect the impact of the meta-analytical results. Once further studies are available, including one by the review authors, an update to this qualitative review and inclusion of a quantitative meta-analysis will be conducted.

Nonetheless, there were also a number of strengths to the studies included. Most of the studies used robust dyslexia criteria, often citing the DSM or ICD and using conservative diagnostic cut-off scores such as ≥ 1.5 or ≥ 2 standard deviations. Studies also generally matched groups on important covariates known to impact on reading development, such as age and intelligence, which would otherwise be likely to result in confounding of intervention findings. Across the three intervention groups, intervention durations were brief, 1–30 h for visual perceptual training, 6.3–35 hours for RAPs, and only 12–13.3 h for AVGs. This would suggest that visuo-attentional intervetions may prove to be efficacious much more quickly than other current, more tradtional and time-intensive intervention options (Gabrieli, 2009). Further investigation into whether longer durations of visuo-attentional intervention would increase efficacy would be beneficial.

5. Conclusions

The results of this review show that visuo-attentional interventions for dyslexia, though brief, are able to produce significant reading gains, without the need for explicit phonological or orthographic instruction, and for VPT and AVGs, also without any reading component. The patterns of evidence show that VPT programs provide most benefit for reading fluency and comprehension, visually-based RAPs appear to improve reading accuracy and rate, while AVGS result in gains to reading rate and fluency. Moreover, improvements following visuo-attentional interventions are generally equal to or greater than other intervention options. The current literature, while limited, also suggests that visuo-attentional interventions can produce reading improvements that are maintained for at least two months following treatment and may also improve the reading skills of typically developing children. Emergent evidence also indicates that visuo-attentional interventions benefit reading outcomes in both shallow and deep orthographies.

Additional high quality studies are needed to compare visuo-attentional treatments to both control and established comparison treatments and, importantly, to permit meta-analysis and further establish treatment efficacy in dyslexia. Investigations should also aim to assess intervention benefit on a wide range of reading outcomes over longer time using larger samples to better establish the duration and breadth of benefit to reading skills. While AVGs and VPT specifically target visuo-attentional mechanisms, further investigation into the various higher-level cognitive contibutions in visually-based RAPs is also needed to better elucide the role of visuo-attentional mechanisms in most cognitive activities. In sum, visuo-attentional interventions can be considered effective options for treating dyslexia in childhood. From a clinical perspective, while phonologically-based interventions are efficacious for young children as they remediate single word accuracy and letter-sound knowledge (i.e., skills important for learning to read), computerized visuo-attention interventions may be more efficacious to children who need to develop automaticity (i.e., rate and fluency) as required to become a proficient reader. The evidence obtained from the studies included in this review indicates that visuo-attentional deficits are contributing factors of dyslexia.

Conflicts of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.neubiorev.2019.02.015.

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Appendix G – Chapter Two: Supplementary Information

Table S1.

PRISMA checklist

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	1
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	2-6
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	7
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	7
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	7
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	8
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	8
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	9
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	10
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	10
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	10-11
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	10
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	N/A
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	N/A
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	N/A
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	12
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	Table 3
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	Tables 1 and 2
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	Table 4
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	N/A
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	N/A
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	N/A
DISCUSSION			

Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	17
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	25
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	27
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	28

Table S2.

Additional Outcomes of the Included Studies

#	Citation	Intervention Group *N* and Description	Phonological and Pseudoword Decoding Outcomes	Visuo-Attention Outcomes	Other Outcomes
1	Das-Smaal et al., 1996	Treatment Group n = 17 with DD Multiletter Reading Acceleration Program Active Control Group n = 16 with DD Computerized maths and motor finger exercises	Pseudoword Reading Accuracy - Both groups improved significantly following treatment, $p < .05$ Pseudoword Reading Rate - Neither group improved significantly following treatment, $p < .01$ Pseudoword Reading Fluency - The treatment group improved significantly more than controls following treatment, $p < .05$		Multi-letter unit identification accuracy – Both groups improved significantly following treatment, p < .01 Multi-letter unit identification rate – The treatment groups improved significantly more than the control group following treatment, p < .01
2	Facoetti et al., 2003	Treatment Group n = 12 with DD Standard lateral presentation VHSS Comparison Group n = 12 with DD Speech Training		Covert visual attention orienting – Only the VHSS group showed a significantly increased inhibition effect following treatment, $p <.02$	
3	Franceschini et al., 2013	Treatment Group n = 10 with DD AVG Active Control Group n = 10 with DD NAVG	Pseudoword Decoding Rate (a composite of the 3 pseudoword tasks) - only the AVG group improved significantly following treatment, p =.01, estimated SMD = 1.04 Pseudoword Decoding Accuracy – Analyses not provided Pseudoword decoding fluency(ratio between speed and accuracy	Focused Visual Spatial Attention – only the AVG group improved significantly following treatment, p =.02 Distributed visual spatial attention - only the AVG group improved significantly following treatment, p	

			comprised of a composite of the 3 pseudoword tasks) - only the AVG group improved significantly following treatment, p <.01, SMD = 1.49 Phonological awareness - syllabic blending – neither groups improved following treatment $p > .05$ Two months after treatment, 6 of the 10 AVG group were retest on pseudoword decoding measures. No significant differences between their immediate post-test scores and 2 month follow up scores were found, suggesting long-lasting improvement.	=.03 Cross-modal attention - only the AVG group improved significantly following treatment, p =.05
4	Franceschini et al., 2017a Experiment 2	N = 13 with DD No Treatment followed by the 'The Library Tower' Reading Acceleration Program	Pseudoword Decoding Accuracy - Participants did not significantly improve following either treatment phase, p = .653, SMD = 0.23 Pseudoword decoding rate – Participants improved significantly only following RAP treatment, p = .014, SMD = 0.58 Phonological awareness - pseudoword repetition – Participants significantly improved only following RAP treatment, p = .002	Navon multiple stimuli naming task – Only RAP training significantly improved local before global perception, p = .049

5	Franceschini et al., 2017a Experiment 4	Treatment Group *n* = 7 with DD AVG Active Control Group *n* = 7 with DD NAVG	Pseudoword decoding accuracy - – Neither the AVG nor NAVG groups improved significantly following treatment, $p > .05$ Pseudoword decoding rate **-** Only the AVG group improved significantly following training, $p = .032$	Navon task – Only the AVG group demonstrated a significant decrease in local influence on global task, $p = .022$; and significant increase of global interference on the local task, $p = .017$
6	Franceschini et al., 2017b	Treatment Group *n* = 16 with DD AVG Active Control Group *n* = 12 with DD NAVG	Pseudoword decoding rate - only the AVG group improved significantly following training, $p = .02$, SMD = 0.98 Pseudoword decoding accuracy - neither AVG nor NAVG improved significantly Auditory-phonological working memory -only the AVG group improved significantly following training, $p = .03$, SMD = 0.9	Focused visual spatial attention - only the AVG group improved significantly following training, $p = .04$, SMD = 0.85 Distributed visual spatial attention - neither AVG nor NAVG improved significantly Visual, auditory, and visual-auditory processing - neither AVG nor NAVG improved significantly Cross-sensory attention shifting - only the AVG group showed significant reductions in their visual- to-auditory shift cost following training, $p = .045$, SMD = 0.47. Neither group showed significant reductions in their auditory-to-visual shift cost following training

7	Gori et al., 2016 Experiment 3	$N = 11$ with DD NAVG followed by AVG	Pseudoword decoding fluency - Participants improved significantly only following AVG treatment, $p = .038$ Pseudoword repetition - Participants improved significantly only following AVG treatment, $p = .044$	Coherent dot motion - Participants improved significantly only following AVG treatment, $p = .045$ Illusory motion - Participants improved significantly only following AVG treatment, $p = .038$ Parvocellular-ventral task – participants did not improve following either treatment phase, $p > .05$	
8	Judica et al., 2002	Treatment Group $n = 9$ with DD 'Tachistoscopio' Reading Acceleration Program Control Group $n = 9$ with DD No treatment provided	Pseudoword decoding accuracy – Only the treatment group improved significantly following treatment, $p < .05$, SMD = 1.27 Pseudoword decoding rate - Only the treatment group improved significantly following treatment, $p < .05$, SMD = 0.33 Homophonic word correction accuracy – Neither group improved following the treatment period, $p > .05$, SMD = 0.63 Lexical decision accuracy – Only the treatment group improved significantly following treatment, $p <$	Eye movements during reading – Both groups demonstrated significantly decreased number and amplitude of rightward saccades and regressive movements following the treatment period. Only the treatment group demonstrated significantly reduced fixation durations following the treatment period, $p < .025$ • Number of rightward saccades: SMD = 0.04 • Number of regressions: SMD = - 0.08 • Amplitude of rightward saccades: SMD = 0.32	Vocal reaction times and accuracy during reading – Only the treatment group improved significantly following the treatment period, $p < .05$ Reaction Time: • 2 letters: SMD = 0.81 • 3 letters: SMD = 0.69 • 4 letters: SMD = 0.59 • 5 letters: SMD = 0.59 Accuracy: • 2 letters: SMD = 1.51 • 3 letters: SMD = 2.02 • 4 letters: SMD = 0.82 • 5 letters: SMD = 3.09

			.05, SMD = 0.40 Lexical decision rate – Only the treatment group improved following treatment period, $p < .001$, SMD = 0.87	Fixation duration: SMD = 0.88	
9	Lawton, 2004	Treatment Group n = 18 with DD 'Moving to Read' DDT Active Control Group n = 9 with DD Word Discrimination Game Control Group n = 6 with DD No Treatment			Spelling - The DDT group improved significantly more than the other groups following training, $p = .038$, SMD (DDT & Word Game) = 0.80; SMD (DDT & No Treatment) = 1.20 Processing speed - The DDT group improved significantly more than the other groups following training, $p = .028$, SMD (DDT & Word Game) = 1.10; SMD (DDT & No Treatment) = 1.00
10	Lawton, 2008	Treatment Group n = 15 with DD 'PATH to Reading' DDT of between two and six replications Treatment Comparison Group n = 15 TD PATH to Reading' DDT of between two and six replications			Filtered text reading rate – both groups and all three grade levels ($n = 5$ in each sub group) improved significantly following treatment, $p < .001$ Reading fluency across treatment frequency - reading rate in both increased significantly as treatment frequency increased, $p < .001$

11	Lawton, 2016	Treatment Group $n = 26$ with DD 'PATH to Reading' DDT Comparison Group $n = 6$ with DD 'FastForWord' Auditory Timing Treatment Active Control Group $n = 26$ with DD Linguistic Word Building	Phonological Awareness - The DDT group improved significantly more than the control group following treatment, $p = .0009$	Attention - The DDT group improved significantly more than the control group following treatment, $p = .009$ Direction Discrimination Thresholds – Only the DDT group improved significantly following treatment, $p = 0.014$	Sequential Visual Working Memory – results not provided for pooled sample Non-sequential Visual Working Memory – results not provided Sequential Auditory Working Memory- results not provided Non-sequential Auditory Working Memory - The DDT group improved significantly more than the control group following treatment, $p = .037$ Delayed Recall – results not provided for pooled sample
12	Lawton & Shelley-Tremblay, 2017	Treatment Group $n = 12$ with DD 'PATH to Reading' DDT Treatment Group $n = 9$ TD 'PATH to Reading' DDT Comparison Group $n = 10$ with DD 'Raz-Kids' Guided Reading Comparison Group $n = 11$ TD 'Raz-Kids' Guided Reading	Phonological awareness – Blending words subtest (CTOPP) – Only the DDT groups improved significantly following treatment, $p < .05$	Attention – Stroop and number detection subtests(CAS) – All groups improved significantly following training, $p = .001$	Visual Working Memory - Both DDT groups improved significantly more that the Raz-Kids groups following treatment, $p = .004$ Auditory Working Memory - Both DDT groups improved significantly more that the Raz-Kids groups following treatment, $p = .045$ Delayed Recall – results not provided

13	Lorusso et al., 2004	Treatment Group *n* = 9 with DD Standard Lateral (SL) Presentation 'Flash Word' VHSS Treatment Group *n* = 7 with DD Random Lateral (RL) Presentation 'Flash Word' VHSS Treatment Group *n* = 8 with DD Central (C) Presentation 'Flash Word' VHSS Treatment Group *n* = 6 with DD Central Fixed-Time (CFT) 'Flash Word' VHSS			Global Spelling (a composite of word, pseudoword and sentence writing tasks) – Only the Random Presentation Group and Central Presentation Group improved significantly following treatment, p = .006 and p = .004 respectively • SMD: SL Vs RL = -0.98 SMD: SL Vs C = -0.88 •SMD: SL Vs CFT = 0.31 •SMD: RL Vs C = 0.10 •SMD: RL Vs CFT = 1.30 •SMD: C Vs CFT = 1.19
14	Lorusso et al., 2005	Treatment Group *n* = 6 with DD Standard Lateral Presentation 'Flash Word' VHSS Treatment Group *n* = 6 with DD Random Lateral Presentation 'Flash Word' VHSS	Pseudoword Reading Accuracy – Both groups improved significantly following treatment, p <.001	Visual Spatial Attention Form Resolving Field – The Radom Presentation Group significantly broadened their form resolving field, while the Lateral Presentation Group significantly narrowed their form resolving field, p = .019	
15	Lorusso et al., 2006	Treatment Group *n* = 14 with DD Standard Lateral Presentation 'Flash Word' VHSS Comparison Group *n* = 11 DD Reading-Focused Speech Therapy	Global Phonological Awareness (a composite of blending and elision tasks) – The VHSS Group improved significantly more following treatment, p =.008, SMD = 0.94		Global Spelling (a composite of word, pseudoword and sentence writing tasks) – All groups improved significantly following treatment, p =.001, SMD = 0.43 Global Memory (a composite of short- term, working-, and long-term memory tasks) – The VHSS Group improved

					significantly more following treatment, *p* =.007, SMD = 0.95
16	Lorusso et al., 2011	Treatment Group *n* = 33 with DD (5 L-types, 15 P-types, and 13 M- types) Standard Lateral (SL) Presentation 'Flash Word' VHSS Treatment Group *n* = 22 with DD (5 L-types, 4 P-types, and 13 M-types) Random Lateral (RL) Presentation 'Flash Word' VHSS Treatment Group *n* = 18 with DD (2 L-types, 5 P-types, and 11 M-types) Central Presentation (C) 'Flash Word' VHSS Treatment Group *n* = 15 with DD (1 L-types, 7 P-types, and 7 M-types) Central, Fixed-Time (CFT) 'Flash Word' VHSS Treatment Group *n* = 9 with DD (2 L-type and 7 P-type only) Reversed Lateral Presentation (RevL) 'Flash Word' VHSS	Global Phonological Awareness Score (a composite of phonemic blending and elision tasks) • For the L-type and P-type dyslexics, groups did not differ significantly in improvement following treatment, *p* >.07 For the M-type dyslexics, groups did not differ significantly in improvement following treatment, *p* >.10		Global Spelling Score (a composite of word, pseudoword and sentence writing from dictation tasks) • For the L-type and P-type dyslexics, groups did not differ significantly in improvement following treatment, *p* >.10 • For the M-type dyslexics, there were significant differences between groups following treatment, *p* = .03, with the CP group improving significantly more than average across types of treatment, *p* < .001 Global Memory Score (a composite of short-term, working memory, long- term memory, and verbal learning tasks) • For the L-type and P-type dyslexics, groups did not differ significantly in improvement following treatment, *p* >.10

		Treatment Group *n* = 13 (13 M-types) Right Hemisphere Lateral Presentation (RH) 'Flash Word' VHSS Comparison Group *n* = 13 with DD (3 L-types, 3 P-types, and 7 M-types) Phonological-Based Therapy (Phon)			For the M-type dyslexics, groups did not differ significantly in improvement following treatment, *p* >.10
17	Luniewska et al., 2018	Treatment Group *n* = 27 with DD AVG Comparison Group *n* = 27 with DD Phonological NAVG Control Group *n* = 16 with DD No Treatment	Outcomes compared between AVG and PNAVG groups: • Pseudoword Reading Rate – Both the AVG and PNAVG groups improved following training, *p* = .001, SMD = -0.06 • Pseudoword Reading Fluency (inefficiency)– Both the AVG and PNAVG groups improved following training, P = .001, SMD = -0.10 • Phoneme Deletion – Both the AVG and PNAVG groups improved following training, P = .001, SMD = -0.37 • Vowel Replacement – Both the AVG and PNAVG groups improved following training, P = .001, SMD = 0.00 • Pseudoword Repetition – Both the AVG and PNAVG groups improved following training, P = .001, SMD = -0.16 Outcomes compared between AVG, PNAVG, and control groups:	Outcomes compared between AVG and PNAVG groups: • Selective Attention – Both the AVG and PNAVG groups improved following training, P = .001, SMD = -0.09	Outcomes compared between AVG and PNAVG groups: • Rapid Object Naming - Both the AVG and PNAVG groups improved following training, P = .01, SMD = 0.34 • Rapid Colour Naming – Both the AVG and PNAVG groups improved following training, P = .01, SMD = 0.42 • Rapid Digit Naming – Both the AVG and PNAVG groups improved following training, P = .01, SMD = 0.03 Rapid Letter Naming – Both the AVG and PNAVG groups improved following training, P = .01, SMD = 0.33

			• Word Recognition – No group improved over time, P = .08, SMD (AVG & PNAVG) = 0.08, SMD (AVG & Control) = -0.53 • Pseudoword Decoding - All groups improved significantly over time, P = .003, SMD (AVG & PNAVG) = -0.03, SMD (AVG & Control) = 0.60 Outcomes compared between AVG, PNAVG, and control groups one month following treatment: • Word Recognition – No group improved over time, *p* = .08 Pseudoword Decoding - All groups improved significantly over time, *p* = .003		
18	Meng et al., 2014	Treatment Group n = 9 with DD Texture Discrimination Training Treatment Group n = 9 TD Texture Discrimination Training Control Group n = 9 with DD No treatment Control Group n = 9 TD No treatment		Texture discrimination – Only the treatment groups improved significantly following the treatment period, $p < .05$	Character recognition – no group improved following the treatment period

Note. VHSS = Visual Hemispheric Specific Stimulation; AVG = Action Video Game; NAVG = Non-Action Video Game (Control Treatment); DDT = Direction Discrimination Training; TD = Typically Developing; DD = Developmental Dyslexia; SMD = Standard Mean Difference of change (also referred to as Cohen's d). Where an experimental treatment is compared to a control or comparator, a positive SMD is in favour of the visuo-attention intervention, in studies with more than 2 groups, the SMD is in favour of the first intervention listed. Small = 0.2, medium = 0.5 and large = 0.8 effect sizes respectively.

Table S3
Excluded Visuo-Attentional Intervention Studies

#	Citation	Language	*N*	Age	Interventions	Outcomes	Exclusion Reason
1	Chouake, Levy, Javitt, and Lavidor (2012)	Hebrew	*N* = 35 TD Adults	24 (3)	Magnocellular training (Motion detection task) VS parvocellular training (Control; pattern detection) Vs no training	Accuracy and Reaction Time on a Lexical Decision task	4) population did not meet criteria; Adult population
2	Dodick et al. (2016)	English (USA)	*N* = 327	7.6 (1.1)	Saccadic Training (King-Devick Reading Acceleration Program) Vs Control Treatment	Reading Fluency and Reading Comprehension (WIAT-III), and Rapid Number Naming (King-Devick Test)	4) population did not meet criteria; "...Other than students identified with Individualized Education Programs, other clinical diagnoses related to cognitive development and learning disabilities were not available to the study team because of student and school district privacy policies" (Page 105)
3	Fischer and Hartnegg (2000)	German	*N*=85 with DD	8 - 15	Visual Training (fixation, a saccade, and distractor tasks) Vs Control Group	Eye movements assessed using an overlap prosaccade and a gap antisaccade task	6) outcomes of interest not measured
4	Gori et al. (2016) Experiment 4	Italian	*N* = 29; 11 TD and 18 with DD	22; 20 - 28	Magnocellular Dorsal Training Vs Control Treatment (Card Games) Vs No Treatment	Text reading rate and accuracy, peripheral target perception task, temporal attention task, coherent dot motion task	4) population did not meet criteria; Adult population
5	Heim, Pape-Neumann, van Ermingen-Marbach, Brinkhaus, and Grande (2015)	German	*N* = 45; 10 TD and 35 with DD	9.9 (0.6); 8.7 - 11.2	Attention Treatment (CogniPlus and Celeco) Vs Phonological Vs Reading Vs No Treatment	Reading decoding, recoding, and comprehension (KNUSPEL-L). Attention Treatment Group retested on attention test (KITAP) and Phonological Treatment group retested on phonological test (BAKO 1-4)	4) Population did not meet criteria; Unclear whether the paper excluded other with neurological, neurodevelopmental, or psychological disorders (See footnote 2 on page 2194 of the original article) and contact with author was unsuccessful.

6	Koen (2012)	English (USA)	*N* = 15 with DD	14; 8 - 19	VHSS (Flash Word) Vs No Treatment Control	fMRI data, reading fluency	4) population did not meet criteria; age
7	Koen et al. (2017)	English (USA)	*N* = 15 with DD	8 - 19	VHSS (Flash Word) Vs Waitlist Control	fMRI data, reading fluency	4) population did not meet criteria; age
8	Korinth, Dimigen, Sommer, and Breznitz (2016)	German	*N* = 36	21.92	Reading Acceleration Program: Accelerated Erasure Rate Vs Fixed Erasure Rate	Reading rate and comprehension, eye movements	4) population did not meet criteria; age
9	Korinth and Fiebach (2018)	German	*N* = 25	21.95	Eye movement feedback Vs Control	Reading rate and comprehension, eye movements	4) population did not meet criteria; age
10	Lawton (2001)	English (USA)	*N* = 35 Half TD and half with DD	5 - 8	Magnocellular training (Left-right movement discrimination task)	Reading fluency	7) not enough information provided; Conference abstract
11	Lawton (2002)	English (USA)	*N* = 36 with DD	8 - 11	Magnocellular training (Left-right movement discrimination task) Vs Control Treatment (Word Discrimination task)	Reading rate	7) not enough information provided; Conference abstract
12	Lawton (2004a)	English (USA)	*N* = 108	9 - 10	Magnocellular training (Left-right movement discrimination task) Vs Control Treatment (Word Discrimination task) Vs No Treatment	Reading rate and comprehension, word ID, spelling, and copying	7) not enough information provided; Conference abstract
13	Lawton (2007a)	English (USA)	*N* = 106; 41 inefficient readers 65 efficient readers	7 - 9	'Moving to Read' DDT Vs Word Discrimination (Control) Vs No Treatment	Reading fluency and comprehension, phonological and orthographic skills, sight-word reading, word reading accuracy, spelling, direction discrimination	8)Did not satisfy risk of bias criteria; •Intervention/group classifications – Within the treatment group the intervention was administered at different complexities that was not statistically controlled for. .. Reading ability levels were compared rather than treat groups.

							•Deviations from intervention – Many participants did both treatments or completed a comparison treatment in the middle of the experimental treatment •Reported results – Analyses compared differing levels of treatment complexity and different readers (efficient and inefficient) rather than comparing the groups.
14	Lawton (2007b)	English (USA)	N/A	7	Magnocellular training (Left-right movement discrimination task) Vs Control Treatment (Word Discrimination task) Vs No Treatment	Reading Skills, Contrast Sensitivity	7) not enough information provided; Conference abstract
15	Lawton (2009)	English (USA)	N/A	N/A	Magnocellular training (direction discrimination task) Vs Control Treatment (Word Discrimination task)	Reading rate	7) not enough information provided; Conference abstract
16	Lawton (2011)	English (USA)	*N* = 9 with DD	5 - 9	'Moving to Read' DDT Vs Increased complexity DDT	Computerised reading fluency test, reading comprehension (GSRT), word identification (Dyslexia Determination Test), word reading accuracy and spelling (WRAT3), contrast sensitivity function*;	8) Did not satisfy risk of bias criteria; • Intervention/groups classifications - Not well defined for retrospective group which had participated in two previous studies, two rounds of treatment, and it was not stated why the 6 participants were chosen from the larger number of participants of the previous studies. • Deviations from intervention – At least one participants

							was receiving an additional intervention and it was not clear if others had participated in other interventions between the two rounds of treatment. • Reported results – analyses compared differing levels of treatment complexity rather than comparing the two groups, additional data (typical children) reported in results section that were not reported in method section.
17	Lawton, Conway, and Edland (2014)	English (USA)	*N* = 75 with DD	7 - 8	Visual Training (PATH to Reading; Movement discrimination task) Vs Auditory Training (FastForWord)	reading fluency, attention, and working memory	7) not enough information provided; Conference abstract
18	Leong et al. (2014)	English (USA)	*N* = 76	4 - 8	Saccadic Training (King-Devick Remediation Program) Vs Control Treatment	Reading Fluency (WIAT-III), and Rapid Number Naming (King-Devick Test)	4) Population did not meet criteria; correspondence with author confirmed that diagnostic information was not collected and all children participated.
19	Peyre et al. (2017)	French	*N* = 11 with DD	7 - 12	Occulomotor Training	Reading, writing, phonological skills, visuo-attention, verbal memory (batterie analytique du langage ecrit; BALE).	1) Not written in English
20	Qian and Bi (2015)	Chinese	*N* = 28; 11 TD and 17 with DD	10.42; 9 - 11	Magnocellular Visual- Motor Intervention Vs No Treatment	Phonological ability, Rapid Naming, Magnocellular Function Test	6) outcomes of interest not measured
21	Solan, Shelley-Tremblay, Ficarra, Silverman, and Larson (2003)	English (USA)	*N* = 30 poor readers	11.3 (0.3)	Attention Therapy (Perceptual Accuracy, Visual Efficiency, Visual Search, Visual Scan, and Visual	Reading comprehension (Gates-MacGinitie Reading Test) and Attention (Cognitive Assessment System)	5) intervention did not meet criteria; Attention therapy included attention span (WM) and was considered

					Span)		too broad
22	Solan, Larson, Shelley-Tremblay, Ficarra, and Silverman (2001)	English (USA)	*N* = 31 with DD	11.4 (0.4)	Eye movement Training Vs Reading Comprehension Therapy	Reading comprehension (Gates-MacGinitie Reading Test) and Eye Movements	4) Population did not meet criteria; "...A visual screening for acuity at far and near, hyperopia, near point phorias, and binocular fusion identified 5 children with visual disorders...” (Page 110)
23	Solan et al. (2004)	English (USA)	*N* = 16 poor readers	12.4 (0.4)	Temporal Visual Processing Therapy Vs No Treatment	Reading Comprehension (Gates-MacGinitie Reading Test) Reading Rate (GORT), Phonological Decoding (Woodcock-Johnson Word Attack Test), coherent motion threshold task	4) Population did not meet criteria; "vision screening identified four children with mild vision disorders. Since the visual deficits were minimal, the students were included in the study...." (Page 643). Also unclear whether the paper excluded other neurological, neurodevelopmental, or psychological disorders and contact with author was unsuccessful.
24	Wang et al. (2014)	Chinese	*N* = 38; 19 TD and 19 with DD	8 - 10	Texture Discrimination Training	stimulus-to-mask onset asynchrony	6) outcomes of interest not measured
25	Wethe, Leong, Pang, and Weil (2012)	English (USA)	*N* = 9	8.4 (1.2)	Saccadic Training (King-Devick Remediation Program)	Reading Fluency (Scholastic Fluency Formula Assessment)	3) study design did not meet criteria; Study did not have a comparator or control group
26	Van Strien, Stolk, and Zuiker (1995)	Dutch	*N* = 40 with DD	10.35	Anxiety-laden word VHSS (HEMSTIM) Vs neutral word VHSS (HEMSTIM)	Text Reading (substantive errors, fragmentations, time; AVI-B)	4) Population did not meet criteria; Paper did not state whether other neurodevelopmental, neurological and visual disorders were screened and excluded for and correspondence with author was unsuccessful.

Table S4. *Additional study information*

Study Details	
Reference	Facoetti et al., 2003 - The role of visuospatial attention in developmental dyslexia
Corresponding Author	Andrea Facoetti (andreafacoetti@unipd.it)
Quality Assessment - Cochrane	
1) Please specify how you decided which treatment each participant should be allocated to (Please specify randomisation method used, if any).	
The two ACTIVE trainings was carried out in two different rehabilitation hospitals, thus, none randomisation method was used and unselected children with dyslexia were treated. The selection criteria of children with dyslexia was the same in the two rehabilitation hospitals.	
2) Please describe all measures taken, if any, to ensure participants and those recruiting participants could not foresee which treatment participants would be assigned to (allocation concealment).	
None, see point 1	
3) Please describe all measures taken, if any, to ensure blinding of participants and key personnel from knowledge of which intervention a participant had received OR which were the target and control interventions (Blinding of participants and personnel).	
The two investigated trainings were target interventions. The children (and their parents) did not know the specific aim of the research. Moreover, children did not see the games played by the other children. Key personnel that administered the games know the difference between the two training, but they did not actively participate to the training (they only monitored that the children played the games) and did not analyse the data.	
4) Please describe all measures taken, if any, to ensure that investigators who assessed outcome measures were blind to which intervention a participant had received (Blinding of outcome assessment).	
The investigators that analysed the data did not know which training was done.	
5) Please indicate whether any participants withdrew from the study and their assigned intervention (attrition), AND whether any available participant data was excluded from data analysis. Please provide reasons for any missing data (Completeness of outcome data).	
for attrition we lacked Four participants in the rapid letter string presentation training and three participants in the speech training . The data of these participants were excluded from data analysis. The missing data were mainly due to fatigue.	
6) Please indicate if this study had a published, pre-specified protocol.	
none	
Data Extraction	
1) Baseline characteristics: Please specify whether statistical comparisons were conducted to ensure groups did not differ on age, IQ, or reading skill at baseline. If conducted, please provide these baseline comparisons, including means, standard deviations and p values.	
2) **Administration:** Please indicate whether participants were provided the intervention individually or as a group	
The two interventions were individually administered	
3) **Location:** Please indicate the location of where the interventions took place (e.g., school, hospital etc)	
Rehabilitation hospital	
4) **Outcome Data:** Please provide pre- and post-intervention [SD’s] for each group, for each outcome measure	
Too much time is passed; I worked on this research project about twenty years ago, I am sorry.	

Can you estimated these data from published data?
5) **Outcome Data:** If possible, for each outcome measured, please provide the Standardized Mean Difference of Change Formula for independent sample: (T2-T1 means of Experimental group) – (T2-T1 means of control group)/(pooled standard deviation)
See previews point
6) **Timeframe of Outcome Measures**: Please indicate the timeframe between when the **pre-test** was conducted and beginning of training
From two to seven days
7) **Timeframe of Outcome Measures:** Please indicate the timeframe between when the **post-test was** conducted and the conclusion of training
From two to seven days

Table S5. *Additional study information*

Study Details	
Reference	Franceschini et al., 2013 - Action video games make dyslexic children read better
Corresponding Author	Andrea Facoetti (andreafacoetti@unipd.it)

Data Extraction

1) **Outcome Data:** If possible, for each outcome measure, please provide the Standardized Mean Difference of Change

<u>Formula for independent sample:</u>

(T2-T1 means of Experimental group) − (T2-T1 means of control group)/(pooled standard deviation)

	T1-T2 comparisons	(speed/accuracy)	Speed	accuracy
Figure 1 panel B	General reading	1,266		
Figure 1 panel E	Pseudo-words reading	1,491		
Figure 1 panel F	Text reading	0,995	0,679	-0,171
Table S3	Clinical pseudo-words list	0,879	0,132	-0,363
	Experimental pseudo-words list	0,780	0,366	-0,664
	Experimental pseudo-words text	0,995	0,785	-0,072
	Experimental words text (text reading)	0,995	0,679	-0,171

2) **Timeframe of Outcome Measures**: Please indicate the timeframe between when the **pre-test** was conducted and beginning of training

From one to three days

3) **Timeframe of Outcome Measures:** Please indicate the timeframe between when the **post-test was** conducted and the conclusion of training

The post-training assessment was conducted one to three days to the end of the training period

4) Please describe all measures taken, if any, to ensure blinding of key personnel and outcome assessors from knowledge of which intervention a participant had received OR which were the target and control interventions (Blinding of participants and personnel).

The children (and their parents) did not know the specific aim of the research (study the difference of action and non action video games on attentional and reading skills). Moreover, children did not see the mini-games played by the other children. Key personnel that administered the mini-games know the difference between the two

training, but they did not actively participate to the training (they only monitored that the children played the mini-games) and did not analyse the data.
The researcher that analysed the data did not know which of the two groups played the action or non action mini-games.

Table S6. *Additional study information*

Study Details	
Reference	Franceschini et al., 2017 - A different vision of dyslexia: Local precedence on global perception
Corresponding Author	Sandro Franceschini (sandro.franceschini@unipd.it)
Experiment 2: Global visual perception in children with dyslexia after a visual treatment	
Quality Assessment - ROBINS	
1) Please describe all measures taken, if any, to ensure that investigators who assessed outcome measures were blind to which intervention a participant had received. If no measures were used to ensure blinding, please indicate whether knowledge of intervention OR study aims could have biased the outcome assessment. Please also indicate if alternative forms of the outcome measures were used to reduce the impact of test familiarity and practice effects	
In this experiment the investigators were not blind to the intervention. The investigator that analysed the data was not the same that collected the data in the different phases of the training. The tasks used to evaluate reading abilities were the same in the three phases of the research. To reduce the impact of test familiarity also two standardized measures of reading skills on different text passages were taken "To confirm the results about reading speed improvement, in T2 and T3, we administered two standardized reading texts. T-test comparisons on reading speed revealed an improvement between T2 (z score mean=-2.12, SD=1.11) and T3 (z score mean=-1.84, SD=.92; t(12)=-2.104, p=.03 , Cohen's d=.28, B_{01}=1.59), without changes in reading accuracy from T2 (z score mean=-1.64, SD=1.98) to T3 (z score mean=-1.25, SD=2.74; t(12)-.57, p=.579 , Cohen's d=.17, B_{01}in favor of the null=2.42). (supplementary information)"	
2) Please indicate if this study had a published, pre-specified protocol.	
No	
Data Extraction	
1) **Location:** Please indicate the location of where the interventions took place (e.g., school, hospital etc)	
The intervention took place in a rehabilitation centre.	
2) Duration of Intervention/s:please specify the number and duration of intervention sessions, and total amount of intervention received. Please also specify the duration of the no treatment period.	
The training phase (period between T2-T3) lasted 10 days (10 sessions) distributed across two or three weeks, in daily sessions of about 40 minutes. The no training phase (time between T1 and T2) was of the same duration.	
3) **Outcome Data:** If possible, for each outcome measure, please provide the Standardized Mean Difference of Change <u>Formula for independent sample:</u> (T2-T1 means of Experimental group) – (T2-T1 means of control group)/(pooled standard deviation)	

Applying the suggested formula (<u>but remember that in this experiment we are speaking about dependent samples</u>): *Word text reading speed (T2-T3 means of Experimental group) − (T2-T1 means of the same control group)/(pooled standard deviation)= .29* *Word text reading accuracy=.55* Phonological decoding (i.e. pseudowords reading) speed =.58 Phonological decoding accuracy =.23
For other measure of Cohen's d see also SI *Training effect on reading skills* In order to evaluate the effects of RAP training [29] on reading skills, we conducted four different ANOVAs on response time (in sec) and errors (number) as dependent variables, and with time (T1, T2 and T3) as within-subject factor. Words text reading:the ANOVA on the speed of words text reading revealed a significant effect of time ($F_{(1.138,13.658)}$=4.545, p=.048 η^2=.275). Paired sample t-test showed that differences were significant only between T2-T3 (see main text) and T1-T3 (T1 mean=343 sec, SD=270; $t_{(12)}$=2.187, p=.049, Cohen's d=.61, B_{01}=1.77; T1-T2 $t_{(12)}$=1.643, p=.126, Cohen's d=.17, B_{01}in favor of the null=1.06). A second ANOVA on errors, showed no significant effects ($F_{(2,24)}$=.926, p=.41, η^2=.072). Words text reading errors were not influenced by the treatment (T1 mean=12, SD=12; T2 mean=11, SD=11; T3 mean=13, SD=16). The improvement in text reading speed was not explained by a speed/accuracy trade-off effect. Two months after the end of RAP training (T4), the same group of children with dyslexia was again evaluated in their words text reading abilities: no significant difference between T4 (mean=252 sec, SD=177) and T3 was found in reading speed ($t_{(12)}$=-.799, p=.44, Cohen's d=.22, B_{01}in favor of the null=2.17) or accuracy ($t_{(12)}$=1.484, p=.164 , Cohen's d=.41, B_{01}in favor of the null=1.25; T4 mean=8.68, SD=10.42). These findings showed that the reading improvement was still maintained, demonstrating a long lasting effect of the brief and intensive RAP training. To confirm the results about reading speed improvement, in T2 and T3, we administered two standardized reading texts. T-test comparisons on reading speed revealed an improvement between T2 (z score mean=-2.12, SD=1.11) and T3 (z score mean=-1.84, SD=.92; $t_{(12)}$=-2.104, p=.03 , Cohen's d=.28, B_{01}=1.59), without changes in reading accuracy from T2 (z score mean=-1.64, SD=1.98) to T3 (z score mean=-1.25, SD=2.74; $t_{(12)}$-.57, p=.579 , Cohen's d=.17, B_{01}in favor of the null=2.42). Phonological decoding: we found a significant effect of time also for pseudowords reading speed ($F_{(1.138,16.613)}$=6.479, p=.014 η^2=.351). Paired sample t-test revealed that only T2-T3 (see main text) and T1-T3 (T1 mean=234 sec, SD=87; $t_{(12)}$=2.898, p=0.013, Cohen's d=.69, B_{01}=4.54) were significantly different. Treatment with time constraint significantly improved pseudowords reading speed. Considering errors number as dependent variable, ANOVA results showed no significant changes ($F_{(2,24)}$=.433, p=.653 η^2=.035) in number of errors across the three evaluations, excluding an effect on accuracy. Neither words text reading nor pseudowords reading accuracy were influenced by the treatment. The reading improvements after the visual training were characterized by the increased reading speed without any cost in accuracy.

4) **Timeframe of Outcome Measures**: Please indicate the timeframe between when the T1 assessment was conducted and beginning of the no treatment period
There was no time frame between T1 and beginning of "no training period". We could postponed the evaluation for a maximum of three days all the T2 (or T3) evaluations hypothetically scheduled during the weekend.
5) **Timeframe of Outcome Measures:** Please indicate the timeframe between when the T2 assessment was conducted and the end of the no treatment period, AND the beginning of the training period.
The timeframe between the end of the no treatment period and the T2 assessment was 1-3 days and the period between T2 assessment and the beginning of the training period was 1-3 days.
6) **Timeframe of Outcome Measures:** Please indicate the timeframe between when the T3 assessment was conducted and the end of the training period.
T3 assessment was conducted one to three days to the end of the training period.
7) **Blinding:** Please describe all measures taken, if any, to ensure blinding of participants and key personnel/outcome assessors from knowledge of which intervention a participant had received OR which were the target and control interventions
No measure was taken.

Study Details	
Reference	Franceschini et al., 2017 - A different vision of dyslexia: Local precedence on global perception
Corresponding Author	Sandro Franceschini (sandro.franceschini@unipd.it)

Experiment 4: Global visual perception in children with dyslexia after an action video game training

Quality Assessment – Cochrane
1) Please specify how you decided which treatment each participant should be allocated to (Please specify randomisation method used, if any).
They were randomized in the two group of training, associating the label (1,2,3,4…) assigned to each child to a list of 1 (AVG) or 2 (NAVG) distributed in random order by SPSS program.
2) Please describe all measures taken, if any, to ensure participants and those recruiting participants could not foresee which treatment participants would be assigned to (allocation concealment).
It was not possible for participants (and their parents), and for who recruited the participants to know the assignation group. There was no contact between the groups developer and the structure where children were selected.
3) Please describe all measures taken, if any, to ensure blinding of participants and key personnel from knowledge of which intervention a participant had received OR which were the target and control interventions (Blinding of participants and personnel).

The children (and their parents) did not know the specific aim of the research (study the difference of action and non action video games on attentional and reading skills). Moreover, children did not see the mini-games played by the other children. Key personnel that administered the mini-games know the difference between the two training, but they only monitored that the children played the mini-games and did not analysed the data. Who administered the training was not the same person that evaluated the cognitive/reading skills of the participants.
4) Please describe all measures taken, if any, to ensure that investigators who assessed outcome measures were blind to which intervention a participant had received (Blinding of outcome assessment).
None
5) Please indicate if this study had a published, pre-specified protocol.
No
Data Extraction
8) Baseline characteristics: Please specify whether statistical comparisons were conducted to ensure groups did not differ on age and IQ at baseline. If conducted, please provide p values.
As in other experiments, the inclusion criteria for this study was “normal IQ (≥85)”. No other information was collected. Age was significantly different between the two groups (AVG mean= 11.7, DS=1.3; NAVG mean=9.1; DS=.8), $t_{(12)}$4.567, p=.001).
9) **Location:** Please indicate the location of where the interventions took place (e.g., school, hospital etc)
The intervention was conducted inside a clinical centre in the North of Italy
10) **Outcome Data:** Please specify whether the tasks (words text, pseudowords lists and pseudowords texts) were analysed separately or collapsed to a single measure of speed/ number of errors in the below analyses. Reading speed (syllables per second) improvement was evaluated in AVG and NAVG groups by two separate ANOVAs 2 times (T1 = before and T2 = after) × 3 tasks (words text, pseudowords lists and pseudowords texts). Results showed a significant main effect of time ($F_{(1,6)}$ = 7.78, p = 0.032 η_2 = 0.565; T1 mean = 1.59 SD = 0.41, T2 mean = 1.86, SD = 0.49) only in the AVG training group (NAVG time effect $F_{(1,6)}$ = 1.097, p = 0.335 η_2 = 0.155 T1 mean = 1.29 SD = 0.73, T2 mean = 1.37, SD = 0.65). The same ANOVAs considering as dependent variable the number of errors, did not show any significant effect (AVG time effect $F_{(1,6)}$ = 1.931, p = 0.214 η_2 = 0.243; T1 mean = 4.48 SD = 2.99, T2 mean = 4.21, SD = 3.09; NAVG time effect $F_{(1,6)}$ = 0.692, p = 0.437 η_2 = 0.103; T1 mean = 7.02 SD = 4.68, T2 mean = 6.99, SD = 3.42). The reading improvements after the AVG training were characterized by the increased reading speed without any cost in accuracy[8,13,33] and this result is in agreement with the improved speed of processing already found associated with AVG[32].

The performance in the reading tasks were analysed as three separate measure inside the same ANOVA “2 times (T1 = before and T2 = after) × 3 tasks (words text, pseudowords lists and pseudowords texts)”. Speed and number of errors were analysed separately.
11) **Outcome Data:** If possible, for each outcome measure, please provide the Standardized Mean Difference of Change Formula for independent sample: (T2-T1 means of Experimental group) − (T2-T1 means of control group)/(pooled standard deviation)
SMD Syll/sec=1.207 SMD errors=.8 09 I found an error in the text of sci rep, here you find the correct value “The same ANOVAs considering as dependent variable the number of errors, did not show any significant effect (AVG time effect $F_{(1,6)} = 1.931$, $p = 0.214$ $\eta_2 = 0.243$; T1 mean = 4.28 SD = 3.41, T2 mean = 5.43, SD = 3.89; NAVG time effect $F_{(1,6)} = 0.692$, $p = 0.437$ $\eta_2 = 0.103$; T1 mean = 8.14 SD = 6.07, T2 mean = 7.24, SD = 3.79).”

Table S7. *Additional study information*

Study Details	
Reference	Franceschini et al., 2017 – Action video games improve reading abilities and visual-to-auditory attentional shifting in English-speaking children with dyslexia
Corresponding Author	Sandro Franceschini (sandro.franceschini@unipd.it)
Quality Assessment – Cochrane	
1) Please specify how you decided which treatment each participant should be allocated to (Please specify randomisation method used, if any).	
Children were assigned to one of the two trainings randomly. The training (randomly extracted) started as soon as a mini group of four children was formed (this number was chosen for daily activity organization).	
2) Please describe all measures taken, if any, to ensure participants and those recruiting participants could not foresee which treatment participants would be assigned to (allocation concealment).	
Parents had no idea what treatment would be proposed to their children	
3) Please describe all measures taken, if any, to ensure blinding of participants and key personnel from knowledge of which intervention a participant had received OR which were the target and control interventions (Blinding of participants and personnel).	
The children (and their parents) did not know the specific aim of the research (study the difference of action and non action video games on attentional and reading skills). Moreover, children did not see the mini-games played by the other children. Key personnel that administered the mini-games know the difference between the two training, but they only monitored that the children played the mini-games and did not analysed the data. The researcher that analysed the data did not know what of the two groups played the action or non action mini-games.	
4) Please indicate if this study had a published, pre-specified protocol.	
No	
Data Extraction	
1) Baseline characteristics: Please specify whether statistical comparisons were conducted to ensure groups did not differ on IQ at baseline. If conducted, please provide p value.	
Intelligence quotient was most of the cases reported in the diagnosis certification defined as "inside the normal range" or greater than 85.Consequently, no analysis was conducted.	
2) **Location:** Please indicate the location of where the interventions took place (e.g., school, hospital etc)	
The interventions took place at the Sydney university	
3) **Other:**How was the diagnosis of dyslexia for each participant confirmed? E.g., was documented evidence of diagnosis cited?	
A specific questionnaire about the presence of developmental dyslexia was administered to the parents of children, and a certification of reading difficulties was requests.	

Table S8. *Additional study information*

Study Details	
Reference	9. Judica et al., 2002 - Training of developmental surface dyslexia improves reading performance and shortens eye fixation duration in reading
Corresponding Author	Pierluigi Zoccolotti (pierluigi.zoccolotti@uniroma1.it)

Quality Assessment - ROBINS

1) Please describe all measures taken, if any, to ensure that investigators who assessed outcome measures were blind to which intervention a participant had received. If no measures were used to ensure blinding, please indicate whether knowledge of intervention OR study aims could have biased the outcome assessment.

Speech therapists carried out the intervention sessions. Two different investigators examined the children in the pre- and post- tests: one carried out the standard tests (reading batteries) and one the experimental tests (eye movement recordings during reading, and vocal reaction times during reading). As for the standard tests - a reading achievement battery (MT Reading Test), and the Developmental Dyslexia and Dysorthography (DDD) battery – the investigator was not blind to the intervention; the outcomes of these tests were objective measures of reading speed and accuracy. As for the experimental tests, eye movements and vocal reaction time measures were collected and analysed by an experimenter who was blind to which intervention a participant had received.

2) Please indicate if this study had a published, pre-specified protocol.

n.a.

Data Extraction

5) **Outcome Data:** If possible, for each outcome measure, please provide the Standardized Mean Difference of Change

Formula for independent sample:

(T2-T1 means of Experimental group) − (T2-T1 means of control group)/(pooled standard deviation)

PLEASE NOTE THAT SMD NEGATIVE VALUES = BETTER PERFORMANCE for the standard reading tests (that is, less time to read or lower number of errors), and for the vocal reaction time test (both RTs and accuracy scores).

STANDARD READING TESTS outcome measures:

- Time **-0,452** and accuracy **-0,882** (passage reading)
- Time **-0,381** and accuracy **-0,641** (word lists reading)
- Time **-0,327** and accuracy **-1,272** (non-word lists reading)
- Accuracy **-0,636** (homophones lists reading)
- Time **-0,868** and accuracy **-0,403** (lexical decision)

EXPERIMENTAL COMPUTERIZED READING TESTS outcome measures: • Vocal reaction time and accuracy (reading lists of single words) **-0,813** RT 2-lett **-0,697** 3-lett **-0,596** 4-lett **-0,590** 5-lett **-1,512** Accuracy 2-lett **-2,029** 3-lett **-0,822** 4-lett **-3,092** 5-lett • EYE MOVEMENTS recordings (passage reading) **PLEASE NOTE THAT, FOR EYE MOVEMENTS, THE DIRECTION OF THE SMD DEPENDS UPON THE MEASURED PARAMETER, AS INDICATED IN DETAIL BELOW.** - Number of rightward saccades **-0,037 (negative = better)** - Number of regressions **0,085 (negative = better)** - Amplitude of rightward saccades **0,327 (positive = better)** - Fixation duration (eye movement recordings – passage reading) **-0,880 (negative = better)**
6) **Timeframe of Outcome Measures**: Please indicate the timeframe between when the **pre-test** was conducted and beginning of training
1 month or less
7) **Timeframe of Outcome Measures:** Please indicate the timeframe between when the **post-test was** conducted and the conclusion of training
Two weeks

Table S9. *Additional study information*

Study Details	
Reference	Lawton 2004 – Training directionally selective motion pathways can significantly improve reading efficiency
Corresponding Author	Teri Lawton (tlawton@pathtoreading.com)

Quality Assessment - Cochrane
1) Please specify how you decided which treatment each participant should be allocated to (Please specify randomisation method used, if any).
Subject assignment was randomized, ensuring had matched samples based on standardized tests.
2) Please describe all measures taken, if any, to ensure participants and those recruiting participants could not foresee which treatment participants would be assigned to (allocation concealment).
All students in participating classrooms who returned signed informed consents were included, and randomly assigned to each group.
3) Please indicate whether any participants withdrew from the study and their assigned intervention (attrition), AND whether any available participant data was excluded from data analysis. Please provide reasons for any missing data (Completeness of outcome data).
There was some drop out due to moving away, excessive absences, and physical injuries that damaged visual sensitivity. There was no missing data, since only those who completed their assigned intervention were included in the results.
4) Please indicate if this study had a published, pre-specified protocol.
Yes, since it was funded by an SBIR grant from NICHD.

Data Extraction
1) Baseline characteristics: Please specify whether statistical comparisons were conducted to ensure groups did not differ on age, or IQ, at baseline. If conducted, please provide p values.
IQ was not analysed. Classes at each grade level had students at te same grade level. Since this was conducted in mainstream classrooms, no one with intellectual disabilities was included
2) **Administration:** Please indicate whether participants were provided the intervention individually or as a group
Participants were provided the intervention in small groups from 3-7 students at a time.

3) **Outcome Data:** If possible, for each outcome measure, and comparing each group, please provide the Standardized Mean Difference of Change Formula for independent sample: (T2-T1 means of Experimental group) − (T2-T1 means of control group)/(pooled standard deviation)
Improvements are in terms of words per minute: Reading Rate: Path – NoTraining = 1.98; Path – Word training = 1.80 Improvements are in terms of grade level for the following measures: DDT: Path – NoTraining = 1.3; Path – Word training = 1.1 WRAT Reading: Path – NoTraining = 0.9; Path – Word training = 0.5 WRAT Spelling: Path – NoTraining = 1.2; Path – Word training = 0.8 WISC Copying: Path – NoTraining = 1; Path – Word training = 1.1 GSRT: Path – NoTraining = 1.0 ; Path – Word training = 1.4
4) **Timeframe of Outcome Measures**: Please indicate the timeframe between when the **pre-test** was conducted and beginning of training
Within one week
5) **Timeframe of Outcome Measures:** Please indicate the timeframe between when the **post-test was** conducted and the conclusion of training
Within one week
6) Other: -Could you provide the M, SD, and range of the age for the entire sample
Mean age = 7.3 years old, SD = 0.5, Range = 6.1 – 8.2

Table S10. *Additional study information*

Study Details	
Reference	Lawton 2008 - Filtered text and direction discrimination training improved reading fluency for both dyslexic and normal readers
Corresponding Author	Teri Lawton (tlawton@cs.ucsd.edu; tlawton@pathtoreading.com)
Quality Assessment - ROBINS	
1) Please specify which pre-intervention prognostic factors were expected, and/or controlled for (e.g., Age, IQ, and reading ability).	
All children In the class (grades k, 1, 2, and 3) that were able to do the left-right movement discrimination task were included. Both IR and ER were included, this being determined by The Dyslexia Screener, the precursor to the Decoding-Encoding Screener for Dyslexia.	
2) Please specify whether deviations from the target interventions, if any, occurred during the study (e.g., if participants received other interventions during the course of the study, particularly if they participated in multiple studies; if certain participants received extra care/attention not outlined in the intervention)	
As far as we are aware there were no other interventions being used on the children in this study.	
3) Please indicate whether any participants withdrew from the study and their assigned intervention (attrition), AND whether any available participant data was excluded from data analysis. Please provide reasons for any missing data	
No data was excluded from analysis for those following the study protocol (doing left-right movement discrimination once a week). One student moved away so their data was not included.	
4) Please describe all measures taken, if any, to ensure that participants, study personnel, and investigators who assessed outcome measures were blind to which intervention a participant had received. If no measures were used to ensure blinding, please indicate whether knowledge of intervention OR study aims could have biased the outcome assessment.	
All students received the intervention. The experimenter did not know whether a student was dyslexic (treatment) or normal (control) when administering the left-right movement discrimination task or the reading rate task. There was no way for the administration of these two tasks to be biased by the experimenter, since the presentation of stimuli and data collected were done automatically by the computer.	
5) Please indicate if this study had a published, pre-specified protocol.	
There was no published pre-specified protocol, since this was the first study ever conducted to study the improvements in reading following practice on left-right movement discrimination.	
Data Extraction	
1) Baseline characteristics: Please specify whether statistical comparisons were conducted to ensure groups did not differ on IQ at baseline. If conducted, please provide p values.	

No IQ tests were performed, since this is not permissible by the school district.
2) **Administration:** Please indicate whether participants were provided the intervention individually or as a group
The intervention was administered individually in a room just big enough for the experimenter and student, so there were no distractions.
3) **Location:** Please indicate the location of where the interventions took place (e.g., school, hospital etc)
The interventions took place at the elementary school in a room that was converted to a test site for this study.
4) **Duration of Training:** Please specify the duration of each training program, including number of sessions, duration of each session, and period of time that training was conducted, and total time commitment of training. (e.g., 35 sessions x 1 hour, conducted twice weekly for 5 months (Total hours of training = 35 hours)
Each student did between two and six replications, depending on how frequently they participated in this study. During each visit, they would do at least ¼ of a training cycle. Most did ½ a training cycle, each visit taking between 10-15 minutes. Therefore, for the typical student in grades 1-3 who completed 6 replications (training cycles), the training would take a total of 3 hours. For those only completing one replication, the total training time was about 30 minutes. All students included in this study completed between 1-6 training cycles of the intervention, done on subsequent days, spaced at least one week apart.
5) **Outcome Data:** If possible, for each outcome measure, please provide the Standardized Mean Difference of Change between groups Formula for independent sample: (T2-T1 means of Experimental group) – (T2-T1 means of control group)/(pooled standard deviation)
All groups received the intervention training.
6) **Timeframe of Outcome Measures**: Please indicate the timeframe between when the **pre-test** was conducted and beginning of training
Once the pretest (reading rates for both unfiltered and filtered text) was completed, the intervention was started the following week.
7) **Timeframe of Outcome Measures:** Please indicate the timeframe between when the **post-test was** conducted and the conclusion of training
Once the intervention was completed, the post-test was done the following week.

8) Other: -Could you provide the M, SD, and range of the age for the entire sample
Children in this study ranged in age from 5 years to 9 years old. The average age was 7±0.5.

Table S11. *Additional study information*

Study Details	
Reference	Lawton 2016 - Improving Dorsal Stream Function in dyslexics by training figure-ground motion discrimination improves attention reading fluency and working memory
Corresponding Author	Teri Lawton (tlawton@cs.ucsd.edu; tlawton@pathtoreading.com)
Quality Assessment - Cochrane	
1) Please specify how you decided which treatment each participant should be allocated to (Please specify randomisation method used, if any).	
The statistician randomized placement of which children would be in which group, determined by school, from list ordered by DESD score, so would have matched sample, and so each school had children in each group.	
2) Please describe all measures taken, if any, to ensure participants and those recruiting participants could not foresee which treatment participants would be assigned to (allocation concealment).	
Treatment (PATH neurotraining) and Control (FastForWord) were done in different classrooms, whereas Learning Upgrade was done in the student's classroom when the other students were doing the PATH or FFW training. Since they went to different classrooms for different interventions, it was clear which intervention was being done. The staff were assigned to monitor children doing either PATH or FFW training. Standardized testing was done by the entire staff who had no idea what group a student had been assigned to.	
3) Please indicate whether any participants withdrew from the study and their assigned intervention (attrition), AND whether any available participant data was excluded from data analysis. Please provide reasons for any missing data (Completeness of outcome data).	
All data from students who completed the study were included.	
4) Please indicate if this study had a published, pre-specified protocol.	
There was a written protocol for both interventions (PATH and FFW) that staff were instructed to follow.	
Data Extraction	
1) Baseline characteristics: Please specify whether statistical comparisons were conducted to ensure groups did not differ on IQ at baseline. If conducted, please provide these baseline comparisons, including means, standard deviations and p values.	
IQ was not evaluated since that information can not be collected by state law.	

2) **Outcome Data:** If possible, for each outcome measure, please provide the Standardized Mean Difference of Change Formula for independent sample: (T2-T1 means of Experimental group) – (T2-T1 means of control group)/(pooled standard deviation)
3) **Timeframe of Outcome Measures**: Please indicate the timeframe between when the **pre-test** was conducted and beginning of training
Pre-test conducted one week before training began
4) **Timeframe of Outcome Measures:** Please indicate the timeframe between when the **post-test was** conducted and the conclusion of training
Post test conducted one week after training finished
5) Other: - Please provide the age range of the participants. - Please clarify if 'pooled data' relates to the data of all participants/schools. - Please clarify is FastForWord and PATH training were directly compared on outcome measures. If yes, please provide this information. - Please clarify if, in Table 3, the reading speed listed relates to the GORT or the computer-based reading speed assessment.
Age range: 7-8, BAU (Learning Upgrade) 7.3±0.39, PATH- 7.37±0.9, FFW- 7.34±0.27 (M±SD) Pooled data is the data of all participants/schools Do not have data comparing PATH with FFW, done by statistician Table 3 lists reading speed for computer-based reading assessment

Table S12. *Additional study information*

Study Details	
Reference	15. lawton & Shelley-tremblay 2017 - training on movement figure-ground discrimination remediates low-level visual timing deficits in the dorsal stream, improving high-level cognitive functioning, including attention, reading fluency, and working memory
Corresponding Author	Teri Lawton (tlawton@cs.ucsd.edu; tlawton@pathtoreading.com)
Quality Assessment - Cochrane	
1) Please specify how you decided which treatment each participant should be allocated to (Please specify randomisation method used, if any).	
Students reading ability was measured using the DDT. Then subjects were ordered based on their score on the DDT, and assigned first to Raz-Kids, the next to PATH, the next to Raz-Kids, the next to PATH, so order was randomly determined but balanced for reading ability.	
2) Please describe all measures taken, if any, to ensure participants and those recruiting participants could not foresee which treatment participants would be assigned to (allocation concealment).	
All participants were doing reading interventions for most of the study in separate computer rooms, one for each intervention.	
3) Please describe all measures taken, if any, to ensure blinding of participants and key personnel from knowledge of which intervention a participant had received OR which were the target and control interventions (Blinding of participants and personnel).	
Personnel did not know which group a child was assigned to when doing standardized tests. Staff all thought reading stories (Raz-Kids) would be more beneficial in improving reading abilities.	
4) Please indicate if this study had a published, pre-specified protocol.	
There was a written protocol describing how to administer each intervention and training videos for staff and students.	
5) Other: - Please clarify the discrepancy in training times listed in the rationale and method sections. **Rationale:** "...to evaluate whether computer-based neurotraining (PATH to Reading), for 20 min three times/week for 12 weeks,….. computer-based guided reading (Raz-Kids (RK) for 30 min three times/week for weeks." **Method**: "…For 12 weeks, half the second and third grade classes were trained on movement-discrimination and half were trained on RK for a total of 30 min twice a week."	

Students were permitted a total of 30 minutes for the intervention training. Students doing Raz-Kids always completed 30 minutes of training. Students doing PATH training only completed one training cycle, which usually took between 15-20 minutes. When they were done with the training cycle, the computer said "Thank you" showed them how many fish they had earned, a star for each level of complexity they had finished, and their final score, and then quit. These students then returned to the classroom.
Data Extraction
1) Baseline characteristics: Please specify whether statistical comparisons were conducted to ensure groups did not differ on IQ at baseline. If conducted, please provide these baseline comparisons, including means, standard deviations and p values.
IQ was not measured at baseline or at any time, since this test is not permitted to be used.
2) **Location:** Please indicate the location of where the interventions took place (e.g., school, hospital etc)
The interventions took place in two computer labs at the school.
3) **Outcome Data:** If possible, for each outcome measure, please provide the Standardized Mean Difference of Change <u>Formula for independent sample:</u> (T2-T1 means of Experimental group) − (T2-T1 means of control group)/(pooled standard deviation)
That information is contained in Tables 4a and 4b in the paper.
4) **Timeframe of Outcome Measures**: Please indicate the timeframe between when the **pre-test** was conducted and beginning of training
All pretests were completed the week before training began.
5) **Timeframe of Outcome Measures:** Please indicate the timeframe between when the **post-test was** conducted and the conclusion of training
All post-tests were conducted the week following training being completed.
6) **Other:** - Please provide the mean age, SD, and range of the participants as a whole.
8.5 ± 0.5 years, Range was from 7.6 to 9.7 years old

Re: request for further information for a systematic review

Dr. Teri Lawton <tlawton@pathtoreading.com>

Fri 15/06/2018 3:52 PM

To:Jessica Peters <J.Peters@latrobe.edu.au>;

Importance: High

HI Jessica,

I had several publications that had to be submitted in the last two weeks. I will focus on your request tomorrow in between meetings. To answer your question. Yes subjects with these issues were excluded. That only resulted in 1-2 subjects being excluded.

With best wishes, Teri

Dr. Teri Lawton

CEO, Founder, Director of Research Perception Dynamics Institute

Early Childhood Parenting Institute

P.O. Box 231305, Encinitas, CA 92023-1305 (310) 903-6009
www.pathtoreading.com tlawton@pathtoreading.com

On Jun 14, 2018, at 9:59 PM, Jessica Peters wrote:

Dear Dr Lawton,

This email is a friendly reminder to please complete and return the data requests forms regarding your studies that are being included in a systematic review, if you wish to do so, as soon as possible and before the end of June. The information requested pertains to quality assessment and data and will enable us to provide a more comprehensive picture of the current state of research in this area. In order to keep to the efficient timeline for the completion of this review, we will not be able to include any further information provided following the end of June.

There is also some additional information I wished to clarify with you regarding two of your studies, that I had not included in my earlier correspondence. For the papers listed below, did you exclude participants with neurological, psychological, emotional and uncorrected visual disorders, other than dyslexia? I can see this seems to be the common practice in your other papers but was not stated in the 2 listed below.

1. ***Lawton, T. (2016). Improving Dorsal Stream Func'tion in Dyslexics by Training Figure/Ground Mo'tion Discrimina'tion Improves Atten'tion, Reading Fluency, and Working Memory. Fron'tiers in Human Neuroscience, 10, 397. doi:https://dx.doi.org/10.3389/fnhum.2016.00397***
2. ***Lawton, T., & Shelley-Tremblay, J. (2017). Training on Movement Figure-Ground Discrimina'tion Remediates Low-Level Visual Timing Deficits in the Dorsal Stream, Improving High-Level Cogni'tive Func'tioning, Including Atten'tion, Reading Fluency, and Working Memory. Fron'tiers in Human Neuroscience, 11, 236. doi:https://dx.doi.org/10.3389/fnhum.2017.00236***

We appreciate any assistance you are able to provide. warmest regards,

Jessica Peters, BPsychSc (Hons) MPsych (ClinNeuro)

PhD Candidate

Postgraduate Programs Assistant (Wednesdays)

Department of Psychology and Counselling | School of Psychology & Public Health | College of Science, Health & Engineering |

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8/29/2018, 8:48 AM

Fw: request for further information for a systematic review

Jessica Peters

Wed 29/08/2018 8:51 AM

To:Jessica Peters <J.Peters@latrobe.edu.au>;

From: Dr. Teri Lawton <tlawton@pathtoreading.com>

Sent: Friday, 13 July 2018 1:42 AM

To: Jessica Peters

Cc: Sheila Crewther

Subject: Re: request for further information for a systematic review

Hi Jessica,

I will answer each of your questions below. With best wishes,
Teri

Dr. Teri Lawton

CEO, Founder, Director of Research Perception Dynamics Institute
Early Childhood Parenting Institute

P.O. Box 231305, Encinitas, CA 92023-1305 (310) 903-6009
www.pathtoreading.com tlawton@pathtoreading.com

On Jul 12, 2018, at 12:01 AM, Jessica Peters wrote: Dear Dr Lawton,

I had a few additional questions regarding your studies that I hoped you may assist with. I realize you have already spent a great deal of time answering my questions, and I very much appreciate all the additional information you have already provided, and so I hope that these questions are much quicker to answer.

1) 2004 paper: you use the term 'inefficient' rather than dyslexic and I wanted to clarify what what you mean by this term, especially as you use similar diagnostic testing in your other papers to identify dyslexia.

A dyslexia screener was used to determine if a reader was inefficient.

2) 2004 paper: could you clarify how you randomized participants? (e.g., random number generator, coin toss etc)

As students entered into the study (determined randomly) by returning informed consent forms they were assigned sequentially to one of 3 groups, being assigned to the treatment group twice as often as to the other two groups.

3) For all included papers: Did the tests you used to identify dyslexia (e.g., DESD, DDT) use a particular cut-off score to diagnose dyslexia? For instance,

reading 2 years below age or grade level, or performance being 1 SD behind age norms. I am unfamiliar with these tests and am trying to find a way to be able to make comparisons with other studies.

The tests have specific directions for determining the score used to identify as dyslexic from borderline to markedly below normal. Here are the written instructions:

Instructions for Dyslexia Determination Test (DDT) - only difference between DDT and DESD is that the DESD only has 5 words per grade level and the DDT has 10 words at each grade level.

* **Child has 2 sec to say each word.**
* **Reading Grade Level (RGL) is one grade below the grade level where the child(adult) could say 5 words or less. Must have 10 incorrectly pronounced words beginning at reading grade level and above. Child spells odd dyseidetic (DE) words they read correctly beginning at reading grade level and going to lower grade levels. Child spells dysphonetic (DP) words they read incorrectly beginning at their reading grade level and going to higher grade levels.**

1. Write student's name, age, gender, your name, date of testing on both pages.
2. Say: "*I'm going to show you a list of words and I'd like you to read them quickly but correctly. The lists will get harder, and you won't be able to read all the words. That's OK, just do the best that you can.*"
3. Place K (0) of **DDT Stimulus Booklet** in front of student. Say, "*Begin*" if they do not begin on their own.
4. Mark with a check beside each word according to whether the student immediately read the word correctly within 2 seconds (E), or had the correct pronunciation in longer than 2 seconds (P), or did not know the correct pronunciation (U).
5. If the student gets 6 or more correct, then continue to next test, *e.g.*

   Repeat until student misses 6 or more. Then the student's Reading Grade Level (RGL) is the grade level that is one lower. Then keep going until you have 10 missed words at that grade level or above. When writing down the RGL, for K=-1, For IL=0, and for 1U=1.

6. Say "Thank you. You did very well." Put the Encoding sheet in front of the child.
7. Say, "*Now I want you to spell these words (**odd-numbered**) that you just pronounced for me. Do your best to spell them correctly.*" Have them spell these words in the right column.
8. Starting at grade level and working backwards, and using only the words that the student pronounced correctly (Y), use each word in a sentence.
9. Repeat until the student has spelled 10 of the words that were pronounced correctly in 2 seconds.
10. Say "*Now I want you to spell these words not like they are really spelled, but like they sound. For example, if I ask you to spell laugh you should spell it **laf**, not **laugh**. Do you understand*?"
11. Working forwards from the first word that was marked incorrectly (U) at their reading grade level, pronounce these words for the child, and ask him/her to spell the word like it sounds, not like it is actually spelled. Do not use words in a sentence.
12. Repeat until you have asked for the phonetic spelling of 10 words.
13. To determine the raw score, Write the number of words spelled correctly at the bottom of the list times 10%: Spelling Correctly = DE, Spelling Phonetically = DP;

D = RGL - AGL when using percentile above to determine score that goes from 1-6 for DE and DP:

[1:Above Normal, 2: Normal, 3: Borderline, 4:
Mild, 5: Moderate, 6: Markedly Below Normal]

4) 2008 paper: Apologies for the lack of clarity in my initial request regarding the SMD between the experimental and 'control group'. I just meant the 2 groups. I wonder if you might be able to provide the SMD for each outcome measure between the dyslexic and typical group? I looked to see if i could calculate an estimate based on the paper results, but there is not enough information to do so.

I will see if that is possible. That data was collected more than 23 years ago and some data files can no longer be opened.

5) 2016 paper: Are additional analyses available that directly compare the auditory training group and the visual training group on outcome measures following intervention? If yes, could you provide this information and the SMD between PATH and FFW? The paper has enough information for me to retrospectively compare these groups and calculate the SMD, but I did want to email you before running these analyses myself.

I do not have that data and appreciate you doing these analyses.

warmest regards,

Jessica Peters, BPsychSc (Hons) MPsych (ClinNeuro)

PhD Candidate

Level A Associate Lecturer - Postgraduate Programs Assistant (Wednesdays)

Department of Psychology and Counselling | School of Psychology & Public Health | College of Science, Health & Engineering | La Trobe University | Melbourne Campus
E: j.peters@latrobe.edu.au | W: www.latrobe.edu.au/psy

8/29/2018, 8:51 AM

Table S13. *Additional study information*

Study Details	
Reference	Lorusso 2004 - hemispheric, attentional and processing speed factors in the treatment of developmental dyslexia
Corresponding Author	mluisa@bp.lnf.it (M.L. Lorusso).

Quality Assessment - Cochrane
1) Please specify how you decided which treatment each participant should be allocated to (Please specify randomisation method used, if any).
Assignment of children to the different treatment groups was pseudorandom (meaning that children were assigned to the various groups trying to keep the average of the main reading and demographic variables comparable across groups, i.e. complete randomization at the beginning, but ad-hoc assignment when the groups were almost complete so as to have well-balanced groups). So, it was ensured that age, sex, reading level were as homogeneously distributed as possible across groups and indeed, they did not differ on statistical comparisons. Actually, this study was the second step in the series of studies concerning VHSS. After the positive outcome of the first study (Lorusso et al., 2006), further studies were planned to compare different versions of the VHSS treatment (see also Lorusso et al, 2011). Thus, more groups were added, but the methodology for group assignment was roughly the same across all studies (2004, 2005, 2006, 2011).
2) Please describe all measures taken, if any, to ensure participants and those recruiting participants could not foresee which treatment participants would be assigned to (allocation concealment).
Participants were recruited including, without restrictions (apart from inclusion and exclusion criteria), all children who were diagnosed in the period of the study at the Scientific institute E. Medea or Bergamo hospital and for whom treatment was prescribed by the Child Neuropsychiatrist in charge of the diagnosis. The doctor was blind to the type of treatment which would be assigned to the child, and (s)he had no influence on this decision. The participants and their families were informed about the group they had been assigned to, but they had no influence on the choice and were never asked to express a preference.
3) Please describe all measures taken, if any, to ensure blinding of participants and key personnel from knowledge of which intervention a participant had received OR which were the target and control interventions (Blinding of participants and personnel).
The therapists conducting the treatments were informed about the general goals of the study, i.e. comparison of different versions of the treatment, but hey were not aware of the underlying hypotheses. None of the treatments were ever presented as a control treatment. The children and their parents were informed that a comparison of different treatments was taking place and they were told that the goal was to see advantages and disadvantages of the various versions, but none of the treatments was presented as a control treatment and the underlying neuropsychological hypotheses were not illustrated in details, nor was any expectation ever mentioned. Rather, both therapists and participants were aware that the hypothesis was that all treatment may prove effective and that we were interested in understanding what were the different mechanisms underlying improvement in the different groups.
4) Please describe all measures taken, if any, to ensure that investigators who assessed outcome measures were blind to which intervention a participant had received (Blinding of outcome assessment).

The clinical psychologists who assessed the children were not strictly blind to the treatment the children had received but we have no reason to think that they should have had specific expectations about the outcomes of treatment in the different groups. They were only aware of the general purposes of the study , not of the detailed analysis of the implied neuropsychological factors, and considered all treatments as roughly equivalent.

5) Please indicate whether any participants withdrew from the study and their assigned intervention (attrition), AND whether any available participant data was excluded from data analysis. Please provide reasons for any missing data (Completeness of outcome data).

None of the participants was excluded from analysis and none of the recruited children and families withdrew from the study.
There was one missing datum in one of the outcome measures (Mean Global Spelling change-score) due to one of the children (belonging to group 1 = standard lateral presentation) having completed the dictation test at post-test but not at pre-test.

6) Please indicate if this study had a published, pre-specified protocol.

The study had not been pre-registered.
Nonetheless, the protocol had been declared and described at the beginning of the study and specified in the information sheets signed by the parents with informed consent. More precisely, the treatment protocol had been designed as variations of the treatment protocol described by Bakker's group (the exact protocol is found in Bakker, 1990: Neuropsychological treatment of dyslexia. New York: Oxford University Press. The efficacy of the treatment, known as "hemisphere-specific stimulation", had been documented in peer-reviewed articles by Bakker and colleagues: Journal of Learning Disabilities 1990; Journal of Clinical Neuropsychology 1981; Journal of Clinical and Experimental Neuropsychology 1985). A published software had been used (Masutto & Fabbro, 1995. FlashWord: Training neuropsicologico per la dislessia. Gorizia: Ed. Tecnoscuola) and ad-hoc stimulus lists had been prepared and employed based on Bakker, 1990.

The assessment tools employed in the study are all published tests normed on the Italian population, with satisfactory validity and reliability values and widely used to assess reading and spelling abilities at the national level.

Data Extraction

1) Baseline characteristics: Please specify whether statistical comparisons were conducted to ensure groups did not differ on IQ at baseline. If conducted, please provide these baseline comparisons, including means, standard deviations and p values.

Yes, it was ensured that groups did not differ on IQ, although some of the IQ measurements were not available at the beginning of the treatments. Nonetheless, no significant differences were found at tests. In the table below you find means, SDs and standard errors of the various groups, followed by ANOVA and by post-hoc tests (Bonferroni).

	N	Mean (Full-scale IQ)	St. Dev.	St. Error
Lateral	9	104,1111	7,70462	2,56821
Central	8	93,8750	6,03413	2,13339
Random Lateral	7	99,5714	7,76439	2,93466
Central fixed time	5	102,4000	9,28978	4,15452
Totale	29	99,8966	8,27796	1,53718

ANOVA univariata

QI TOT

	Somma dei quadrati	df	Media dei quadrati	F	Sig.
Fra gruppi	482,011	3	160,670	2,796	,061
Entro gruppi	1436,678	25	57,467		
Totale	1918,690	28			

	Group I	Group J	(I-J)	St. error	Sig.
Bonferroni	1,00	2,00	10,23611	3,68356	,061
		3,00	4,53968	3,82032	1,000
		4,00	1,71111	4,22832	1,000
	2,00	1,00	-10,23611	3,68356	,061
		3,00	-5,69643	3,92339	,954
		4,00	-8,52500	4,32167	,358
	3,00	1,00	-4,53968	3,82032	1,000
		2,00	5,69643	3,92339	,954
		4,00	-2,82857	4,43881	1,000
	4,00	1,00	-1,71111	4,22832	1,000
		2,00	8,52500	4,32167	,358
		3,00	2,82857	4,43881	1,000

2) **Intervention Duration:** Please clarify the how many sessions and the total duration of intervention that participants received.

There were a total of 32 individual sessions taking place twice a week and lasting 45 min each, over a 4-month period, for each treatment.

3) **Outcome Data:** If possible, for each outcome measure, comparing each group, please provide the Standardized Mean Difference of Change

<u>Formula for independent sample:</u>

(T2-T1 means of Experimental group) − (T2-T1 means of control group)/(pooled standard deviation)

There were four groups and no group was considered as a control group.
The groups were compared on three outcome measures: global reading accuracy, global reading speed and global spelling accuracy.
In the following tables, you find:

a) Descriptives of change-scores for each group (post-test minus pre-test) (NB meddcorr_ mean accuracy change-score: meddrap = mean speed change score: medddett = mean spelling change score)
b) ANOVA on change-scores
c) T-tests for each pair of groups, for the outcome measure that turned out to be significantly different between groups, i.e. change in global spelling score

Descrittivi

		N	Media	Deviazione std.	Errore std.	Intervallo di confidenza 95% per la media: Limite inferiore	Limite superiore	Minimo	Massimo
meddcorr	1,00	9	1,3570	2,03684	,67895	-,2086	2,9227	-1,11	5,89
	2,00	8	1,1617	1,05404	,37266	,2805	2,0429	-,22	3,06
	3,00	7	1,6229	1,51853	,57395	,2185	3,0273	-,97	3,44
	4,00	6	1,8511	1,39251	,56849	,3898	3,3125	,72	4,33
	Totale	30	1,4658	1,51325	,27628	,9007	2,0308	-1,11	5,89
meddrap	1,00	9	1,0967	1,48045	,49348	-,0413	2,2346	-,91	4,22
	2,00	8	2,0904	,94495	,33409	1,3004	2,8804	,91	3,53
	3,00	7	1,3562	2,29869	,86882	-,7697	3,4821	-2,05	4,46
	4,00	6	2,3867	3,77455	1,54095	-1,5745	6,3478	-,23	10,00
	Totale	30	1,6802	2,15650	,39372	,8750	2,4855	-2,05	10,00
medddet	1,00	8	,7092	1,89503	,67000	-,8751	2,2935	-2,91	3,49
	2,00	8	2,7379	2,12048	,74970	,9651	4,5107	-,32	6,60
	3,00	7	2,5233	1,90780	,72108	,7589	4,2878	,97	6,07
	4,00	6	,0647	,72409	,29561	-,6952	,8246	-,92	1,19
	Totale	29	1,5734	2,05174	,38100	,7929	2,3538	-2,91	6,60

ANOVA univariata

		Somma dei quadrati	df	Media dei quadrati	F	Sig.
meddcorr	Fra gruppi	1,910	3	,637	,257	,856
	Entro gruppi	64,498	26	2,481		
	Totale	66,408	29			
meddrap	Fra gruppi	8,140	3	2,713	,557	,648
	Entro gruppi	126,724	26	4,874		
	Totale	134,865	29			
medddet	Fra gruppi	36,797	3	12,266	3,782	,023
	Entro gruppi	81,073	25	3,243		
	Totale	117,870	28			

(NB meddcorr = mean accuracy change-score: meddrap = mean speed change-score: medddett = mean spelling change-score)

Standardized Mean Difference of Change:
Group 1 vs 2 (Lateral vs central)
Group 1 vs 3 (Lateral vs Random)
Group 1 vs 4 (Lateral vs Central Fixed-time)
Group 2 vs 3 (Central vs Random)
Group 2 vs 4 (Central vs Central fixed-time)
Group 3 vs 4 (Random vs Central fixed-time)

Statistiche di gruppo

	Tipo Tratt.	N	Media	Deviazione std.	Errore std. Media
medddet	1,00	8	,7092	1,89503	,67000
	2,00	8	2,7379	2,12048	,74970

Test per campioni indipendenti

		Test di Levene di uguaglianza delle varianze: F	Sig.	Test t di uguaglianza delle medie: t	df	Sig. (2-code)	Differenza fra medie	Differenza errore standard	Intervallo di confidenza per la differenza al 95%: Inferiore	Superiore
medddet	Assumi varianze uguali	,123	,731	-2,018	14	,063	-2,02875	1,00546	-4,18525	,12775
	Non assumere varianze uguali			-2,018	13,827	,063	-2,02875	1,00546	-4,18779	,13029

statistiche di gruppo

	Tioo Tratt.	N	Med ia	Deviazi on e std.	Errore std. Med ia
medddet	1 ,0 0	8	,7092	1,89503	,6 7000
	3,00	7	2,5233	1,90780	,721 08

Test per campionindipendenti

	Tes t di Levene di uguaglianza delie varianze		Testt di uguaglianza delie medie					Intervallo di co nfidenza per la differenza al 95%	
	F	Sig	t	df	Sig. (2-code)	Differenz a fra medie	Differenza errore standard	Inferiore	Superiore
medddet Ass umi va rianze uguali	,02 4	,880	-1,844	13	,0 88	-1,81417	,98383	-3,93960	,311 27
Non ass umere va rianze uguali			-1,843	12,711	,089	-1,81417	,98430	-3,9 4555	,31721

st atistiche di gruppo

	Tino Tratt.	N	Med ia	Deviazi on e std.	Errore std. Med ia
medddet	1 ,0 0	8	,7092	1,89503	,6 7000
	4,00	6	,06 47	,7240 9	,2956 1

Test per campioniindipendenti

	Test di Levene di uguaglianza delie varianze		Testt di uguaglianza dell e medie					Intervall o di co nfidenza per la differenza al 95%	
	F	Sig	t	df	Sig. (2-code)	Differenza fra medie	Differenza errore standard	Inferiore	Superiore
medddet Ass umi varianze ugua li	2,611	,1 32	,785	12	,448	,6 44 44	,82141	-1,1 4525	2, 43414
Non ass um ere va rianze uguali			,880	9,487	,401	,644 44	,73231	-,9 9928	2,288 17

st atistiche di gruppo

	Tino Tratt.	N	Med ia	Deviazi on e std.	Errore std. Med ia
medddet	2,00	8	2,7379	2,1 20 48	,74970
	3,00	7	2,5233	1,90780	,721 08

Test per campionindipendenti

	Test di Levene di uguaglianza delie va rianze		Testt di uguaglianza dell e medie					Intervall o di co nfidenza per la differenza al 95%	
	F	Sig	t	df	Sig. (2-code)	Differenza fra medie	Differenza errore standard	Inferiore	Superiore
medddet Ass umi varianze ugua li	,042	,841	,205	13	,841	,21458	1,04809	-2,0 4968	2, 4788 4
Non ass umere varianze uguali			,206	12,981	,840	,21458	1,04020	-2,03296	2, 46213

st atistiche di gruppo

	Tioo Tratt.	N	Med ia	Deviazione std.	Errore std. Med ia
medddet	2,00	8	2,7379	2,1 20 48	,7 4970
	4,00	6	,06 47	,72 409	,2956 1

Test per campionindipendenti

	Tes t di Levene di uguaglianza delie varianze		Testt di uguaglianza delie medie					Intervallo di co nfidenza per la differenza al 95%	
	F	Sig	t	df	Sig. (2-code)	Differenz a fra medie	Differenza errore standard	Inferiore	Superiore
medddet Ass umi va rianze uguali	3,738	,077	2,936	12	,01 2	2,67319	,91035	,68971	4,656 68
Non ass umere va rianze uguali			3,317	9,0 40	,0 09	2,67319	,80588	,85140	4,49499

Statistiche di gruppo

	Tipo Tratt.	N	Media	Deviazione std.	Errore std. Media
medddet	3,00	7	2,5233	1,90780	,72108
	4,00	6	,0647	,72409	,29561

Test per campioni indipendenti

		Test di Levene di uguaglianza delle varianze		Test t di uguaglianza delle medie						
									Intervallo di confidenza per la differenza al 95%	
		F	Sig.	t	df	Sig. (2-code)	Differenza fra medie	Differenza errore standard	Inferiore	Superiore
medddet	Assumi varianze uguali	3,893	,074	2,964	11	,013	2,45861	,82962	,63264	4,28458
	Non assumere varianze uguali			3,155	7,918	,014	2,45861	,77932	,65824	4,25898

4) **Timeframe of Outcome Measures**: Please indicate the timeframe between when the **pre-test** was conducted and beginning of training
The children were tested at the beginning of treatment (i.e. maximum 4-5 days before the first training session)
5) **Timeframe of Outcome Measures:** Please indicate the timeframe between when the **post-test was** conducted and the conclusion of training
The children were retested immediately after the end of treatment (again, within 4-5 days from the last treatment session).
6) **Other:** Please provide the mean age and SD of the participants as a whole.
10,35 (1,76)

Table S14. *Additional study information*

Study Details	
Reference	Lorusso 2005 - Tachistoscopic treatment of dyslexia changes the distribution of visual-spatial attention
Corresponding Author	mluisa@bp.lnf.it (M.L. Lorusso).
Quality Assessment - Cochrane	
1) Please specify how you decided which treatment each participant should be allocated to (Please specify randomisation method used, if any).	
The assignment of children to the different treatment groups was not strictly random, but it was ensured that age was homogeneously distributed across groups (group SL, mean age=10.7, *SD*=2.2; group R, mean age=10.8, *SD*=2.7).	
2) Please describe all measures taken, if any, to ensure participants and those recruiting participants could not foresee which treatment participants would be assigned to (allocation concealment).	
Participants were recruited including, without restrictions (apart from inclusion and exclusion criteria), all children who were diagnosed in the period of the study at the Scientific institute E. Medea or Bergamo hospital and for whom treatment was prescribed by the Child Neuropsychiatrist in charge of the diagnosis. The doctor was blind to the type of treatment which would be assigned to the child, and (s)he had no influence on this decision. The participants and their families were informed about the group they had been assigned to, but they had no influence on the choice and were never asked to express a preference.	
3) Please describe all measures taken, if any, to ensure blinding of participants and key personnel from knowledge of which intervention a participant had received OR which were the target and control interventions (Blinding of participants and personnel).	
The therapists conducting the treatments were informed about the general goals of the study, i.e. comparison of different versions of the treatment, but hey were not aware of the underlying hypotheses. None of the treatments were ever presented as a control treatment. The children and their parents were informed that a comparison of different treatments was taking place and they were told that the goal was to see advantages and disadvantages of the various versions, but none of the treatments was presented as a control treatment and the underlying neuropsychological hypotheses were not illustrated in details, nor was any expectation ever mentioned. Rather, both therapists and participants were aware that the hypothesis was that all treatment may prove effective and that we were interested in understanding what were the different mechanisms underlying improvement in the different groups.	
4) Please describe all measures taken, if any, to ensure that investigators who assessed outcome measures were blind to which intervention a participant had received (Blinding of outcome assessment).	
The psychologists who assessed the children were only aware of the general purposes of the study and considered all treatments as roughly equivalent. They belonged to the clinical staff and we have no reason to think that they should have had specific expectations about the outcomes of treatment in the different groups. The assessment of FRF was conducted by a single, trained clinical psychologist who was not involved in the experimental manipulations and was blind to group assignment.	
5) Please indicate whether any participants withdrew from the study and their assigned intervention (attrition), AND whether any available participant data was excluded from data analysis. Please provide reasons for any missing data (Completeness of outcome data).	

None of the participants was excluded from analysis and none of the recruited children and families withdrew from the study. Missing data: no data were missing regarding the outcome variables
6) Please indicate if this study had a published, pre-specified protocol.
The study had not been pre-registered. Nonetheless, the treatment protocols for the two groups were exactly the same described in a previous study and labeled “lateral presentation” and “random lateral presentation” (Lorusso, Facoetti, & Molteni, 2004. Hemispheric, attentional and processing speed factors in the treatment of developmental dyslexia. Brain and Cognition, 55, 341–348). More precisely, the treatment protocol had been designed as variations of the treatment protocol described by Dirk Bakker’s group (the exact protocol is found in Bakker, 1990: Neuropsychological treatment of dyslexia. New York: Oxford University Press. The efficacy of the treatment, known as “hemisphere-specific stimulation”, had been documented in peer-reviewed articles by Bakker and colleagues: Journal of Learning Disabilities 1990; Journal of Clinical Neuropsychology 1981; Journal of Clinical and Experimental Neuropsychology 1985). A published software had been used (Masutto & Fabbro, 1995. FlashWord: Training neuropsicologico per la dislessia. Gorizia: Ed. Tecnoscuola) and ad-hoc stimulus lists had been prepared and employed based on Bakker, 1990. As far as reading assessment is concerned, assessment tools employed in the study are all published tests normed on the Italian population, with satisfactory validity and reliability values and widely used to assess reading and spelling abilities at the national level. As to the measurement of the FRFs (Form-Resolving Fields), the exact procedure had already been described in another paper at the time of publication (Lorusso, Facoetti, Pesenti, Cattaneo, Molteni, & Geiger, 2004: Wider recognition in peripheral vision for Italian dyslexic children common to different subtypes. Vision Research, 44, 2413–2424) and also previously described by Geiger et al., New England Journal of Medicine 1987; Cognitive Brain Research 1992; Vision Research 1994; 1999, etc..
Data Extraction
1) Baseline characteristics: Please specify whether statistical comparisons were conducted to ensure groups did not differ on IQ at baseline. If conducted, please provide p values.
Sorry, I have not been able to find the dataset with the original data, including IQ data.
2) Intervention Duration: Please clarify the how many sessions and the total duration of intervention that participants received.
All treatment programs were carried out in 32 individual sessions taking place twice a week and lasting 45min each, over a four months’ period.
3) **Outcome Data:** If possible, for each outcome measure, please provide the Standardized Mean Difference of Change Formula for independent sample: (T2-T1 means of Experimental group) − (T2-T1 means of control group)/(pooled standard

deviation)
Sorry, I have not been able to find the dataset on which analyses had been conducted. Nonetheless, I copy below some relevant information from the paper: **Reading scores:** signficant main effects of Time (pre- vs. post-test) on word reading speed [*F*(1,10)=7.19, *p*=.023], word reading accuracy [*F*(1, 10)=7.88, *p*=.019], and nonword reading accuracy [*F*(1,10)=38.25, *p*<.001] were found. Time by Group interactions were generally far from significance, although there was a tendency for the SL group to improve more than the R group in nonword reading accuracy [*F*(1, 10)=4.64, *p*=.057]. FRF scores: a significant difference between the two groups in change-scores from pre- to post-test (i.e., post-test scores minus pre-test scores) at 12.5°, on the left side only [the Group by Time by Side interaction was significant only at eccentricity 12.5; F(1,10)=7.81, p=.019]. In particular, the performance of the R group changed from 16.7 (SE=7.15) to 23.3 (SE=6.15) percent correct, while the SL group showed a decrease in the correct recognition rate from 26.7 (SE=.94) to 13.3 (SE=4.22). These results could be described as the R group having "broadened," and the SL group having "narrowed" their FRF on the left side, from pre-test to post-test.

Table S15. *Additional study information*

Study Details	
Reference	21. Lorusso et al., 2006 - Effects of visual vs reading-focused training in dyslexic children
Corresponding Author	mluisa@bp.lnf.it (M.L. Lorusso).
Quality Assessment - Cochrane	
1) Please specify how you decided which treatment each participant should be allocated to (Please specify randomisation method used, if any).	
Assignment of the children to the two groups was (pseudo)randomised, i.e. cases were assigned to the groups on regular turns (chronological order) but a comparable distribution of cases with respect to sex, age and dyslexia subtype was ensured. In fact, the two groups were counterbalanced for sex (12 vs. 10 males and 2 vs. 1 females), and did not differ in chronological age, full IQ, verbal IQ and performance IQ (all *p*s>.05). A chi-square test revealed no significant differences in the distribution of dyslexia sub-types in the two groups (*p* >05). Further, the two groups did not differ in pre-treatment performances, except for the phoneme blending task, where the VHSS group made a larger number of errors as compared with the RT group (*p* < 005). Actually, this study was the first step in the series of studies concerning VHSS. After the positive outcome of this study, further studies were planned to compare different versions of the VHSS treatment (see Lorusso et al, 2004 and 2005). Overall, the methodology for group assignment was about the same across all four studies (2004, 2005, 2006, 2011).	
2) Please describe all measures taken, if any, to ensure participants and those recruiting participants could not foresee which treatment participants would be assigned to (allocation concealment).	
Participants were recruited including, without restrictions (apart from inclusion and exclusion criteria), all children who were diagnosed in the period of the study at the Scientific institute E. Medea or Bergamo hospital and for whom treatment was prescribed by the Child Neuropsychiatrist in charge of the diagnosis. The doctor was blind to the type of treatment which would be assigned to the child, and (s)he had no influence on this decision. The participants and their families were informed about the group they had been assigned to, but they had no influence on the choice and were never asked to express a preference.	
3) Please describe all measures taken, if any, to ensure that investigators who assessed outcome measures were blind to which intervention a participant had received (Blinding of outcome assessment).	
The clinical psychologists who assessed the children were not strictly blind to the treatment the children had received but we have no reason to think that they should have had specific expectations about the outcomes of treatment in the different groups. Rather, they seemed to have a conservative attitude and to believe that the standard treatment could prove more effective than the experimental one (as written on page 201, second paragraph).	
4) Please indicate if this study had a published, pre-specified protocol.	

The study had not been pre-registered.
Nonetheless, the protocol had been declared and described at the beginning of the study and specified in the information sheets signed by the parents with informed consent. More precisely, the experimental treatment protocol had been described by Bakker's group (the exact protocol is found in Bakker, 1990: Neuropsychological treatment of dyslexia. New York: Oxford University Press. The efficacy of the treatment, known as "hemisphere-specific stimulation", had been documented in peer-reviewed articles by Bakker and colleagues: Journal of Learning Disabilities 1990; Journal of Clinical Neuropsychology 1981; Journal of Clinical and Experimental Neuropsychology 1985). A published software had been used (Masutto & Fabbro, 1995. FlashWord: Training neuropsicologico per la dislessia. Gorizia: Ed. Tecnoscuola) and ad-hoc stimulus lists had been prepared and employed based on Bakker, 1990.
The protocol for VHSS was the same that was described in Lorusso et al., 2004 as "standard lateral treatment".

The RT treatment, as specified in the paper (page 202, paragraph describing RT treatment) was a traditional approach to dyslexia treatment and the therapists as a group had discussed and decided what materials and activities to use in the training.

The assessment tools employed in the study are all published tests normed on the Italian population, with satisfactory validity and reliability values and widely used to assess reading and spelling abilities at the national level. Only the battery used for memory assessment (TEMA) was a published version of an English test (TOMAL, Reynolds and Biegler 1995).

Data Extraction
1) **Outcome Data:** If possible, for each outcome measure, please provide the Standardized Mean Difference of Change Formula for independent sample: (T2-T1 means of Experimental group) − (T2-T1 means of control group)/(pooled standard deviation)

TABLE 2

Significance levels (p values) for the main effects (Time and Group) and Group × Time interactions on the global scores (repeated measures ANOVA). Effect sizes (partial eta^2) are reported in brackets

	Time effect		*Group effect*		*Group × Time interaction*	
Tasks	*F(1, 23)*	*p (one-tailed) α = .01*	*F(1, 23)*	*p (two-tailed) α = .01*	*F(1, 23)*	*p (one-tailed) α = .01*
Global accuracy score	9.36	.003 (.289)	8.19	.009 (.263)	18.78	<.001 (.449)
Global speed score	16.32	.001 (.415)	0.03	n.s.	<.001	n.s.
Global spelling score*	11.90	.001 (.351)	1.88	n.s.	1.11	n.s.
Global phonemic awareness error score	64.31	<.001 (.737)	0.90	n.s.	6.81	.008 (.228)
Global memory score	22.69	<.001 (.497)	<.001	n.s.	7.01	.007 (.234)

*for the global spelling score, consider $F(1, 22)$ because of one missing datum.

Outcome measures were the five global scores (global accuracy score, global speed score, global spelling score, global Phonemic awareness error score and Global Memory score).
Change-scores were calculated (post-test minus pre-test global score) and T-tests were computed between the two groups.
See tables below, reporting:

a) Descriptives of change-scores for each group (post-test minus pre-test) (NB meddcorr_ mean accuracy change-score: meddrap = mean speed change score: medddett = mean spelling change-score, meddfon = mean phonemic awareness change-score; meddmem = mean memory change-score)
b) ANOVA on change-scores
c) T-tests (equivalent to ANOVA)

Descrittivi

		N	Media	Deviazione std.	Errore std.	Intervallo di confidenza 95% per la media: Limite inferiore	Intervallo di confidenza 95% per la media: Limite superiore	Minimo	Massimo
meddcorr	,00	11	-,2885	1,19202	,35941	-1,0893	,5123	-2,69	1,50
	1,00	14	1,6750	1,06975	,28590	1,0573	2,2927	-,97	3,06
	Totale	25	,8111	1,48372	,29674	,1986	1,4235	-2,69	3,06
meddrap	,00	11	1,9370	2,46937	,74454	,2780	3,5959	,04	8,88
	1,00	14	1,0883	1,51647	,40529	,2127	1,9639	-2,58	3,06
	Totale	25	1,4617	1,99280	,39856	,6391	2,2843	-2,58	8,88
medddet	,00	10	,9248	1,62372	,51347	-,2367	2,0864	-1,28	3,61
	1,00	14	1,7398	2,01585	,53876	,5758	2,9037	-3,70	4,39
	Totale	24	1,4002	1,87001	,38171	,6106	2,1898	-3,70	4,39
meddfon	,00	11	-2,0000	1,97484	,59544	-3,3267	-,6733	-6,00	,00
	1,00	14	-3,9286	1,71931	,45951	-4,9213	-2,9359	-7,00	-,50
	Totale	25	-3,0800	2,04471	,40894	-3,9240	-2,2360	-7,00	,00
meddmem	,00	11	,1429	,33707	,10163	-,0836	,3693	-,61	,50
	1,00	14	,4992	,33236	,08883	,3073	,6911	-,15	1,18
	Totale	25	,3424	,37384	,07477	,1881	,4967	-,61	1,18

ANOVA univariata

		Somma dei quadrati	df	Media dei quadrati	F	Sig.
meddcorr	Fra gruppi	23,748	1	23,748	18,779	,000
	Entro gruppi	29,086	23	1,265		
	Totale	52,834	24			
meddrap	Fra gruppi	4,436	1	4,436	1,123	,300
	Entro gruppi	90,874	23	3,951		
	Totale	95,310	24			
medddet	Fra gruppi	3,874	1	3,874	1,113	,303
	Entro gruppi	76,556	22	3,480		
	Totale	80,430	23			
meddfon	Fra gruppi	22,911	1	22,911	6,806	,016
	Entro gruppi	77,429	23	3,366		
	Totale	100,340	24			
meddmem	Fra gruppi	,782	1	,782	6,992	,014
	Entro gruppi	2,572	23	,112		
	Totale	3,354	24			

Test per campioni indipendenti

		Test di Levene di uguaglianza delle varianze		Test t di uguaglianza delle medie						
									Intervallo di confidenza per la differenza al 95%	
		F	Sig.	t	df	Sig. (2-code)	Differenza fra medie	Differenza errore standard	Inferiore	Superiore
meddcorr	Assumi varianze uguali	,162	,691	-4,334	23	,000	-1,96348	,45309	-2,90078	-1,02619
	Non assumere varianze uguali			-4,275	20,382	,000	-1,96348	,45925	-2,92032	-1,00665
meddrap	Assumi varianze uguali	,393	,537	1,060	23	,300	,84864	,80087	-,80810	2,50537
	Non assumere varianze uguali			1,001	15,741	,332	,84864	,84771	-,95082	2,64810
medddet	Assumi varianze uguali	,033	,858	-1,055	22	,303	-,81493	,77236	-2,41670	,78685
	Non assumere varianze uguali			-1,095	21,600	,286	-,81493	,74425	-2,36007	,73021
meddfon	Assumi varianze uguali	,671	,421	2,609	23	,016	1,92857	,73926	,39930	3,45784
	Non assumere varianze uguali			2,564	20,001	,019	1,92857	,75212	,35967	3,49747
meddmem	Assumi varianze uguali	,070	,794	-2,644	23	,014	-,35629	,13474	-,63502	-,07755
	Non assumere varianze uguali			-2,640	21,474	,015	-,35629	,13498	-,63661	-,07596

(NB meddcorr = mean accuracy change-score: meddrap = mean speed change score: medddett = mean spelling change-score, meddfon = mean phonemic awareness change-score; meddmem = mean memory change-score)

2) **Age:** please provide the mean age and SD of all participants.

9.84 (2.19)

Table S16. *Additional study information*

Reference	22. Lorusso et al., 2011 - Neuropsychological treatment of dyslexia: Does type of treatment matter?
Corresponding Author	mluisa@bp.lnf.it (M.L. Lorusso).

1) Please specify how you decided which treatment each participant should be allocated to (Please specify randomisation method used, if any).
Assignment of children to the different treatment groups was (pseudo)random, namely, it was ensured that age and sex were homogeneously distributed across groups. Moreover, since some of the groups were to include only specific subtypes of dyslexia, assignment of children to those groups was clearly proceeding with slower pace, depending on what subtype the children were diagnosed to belong during assessment. Furthermore, since the distribution of subtypes is not equal in the population (M-types being more frequent than P-types, who are also slightly more frequent than L-types), subgroups addressing more infrequent subtypes were filled more slowly.
2) Please describe all measures taken, if any, to ensure participants and those recruiting participants could not foresee which treatment participants would be assigned to (allocation concealment).
Participants were recruited including, without restrictions (apart from inclusion and exclusion criteria), all children who were diagnosed in the period of the study at the Scientific institute E. Medea or Bergamo hospital and for whom treatment was prescribed by the Child Neuropsychiatrist in charge of the diagnosis. The doctor was blind to the type of treatment which would be assigned to the child, and (s)he had no influence on this decision. The participants and their families were informed about the group they had been assigned to, but they had no influence on the choice and were never asked to express a preference.
3) Please describe all measures taken, if any, to ensure that investigators who assessed outcome measures were blind to which intervention a participant had received (Blinding of outcome assessment).
The psychologists who assessed the children were not strictly blind to the treatment the children had been assigned to, but they were not precisely informed (they knew which therapist had been treating the participant, but since all therapists were delivering all kinds of treatments, this was not informative). They were aware of the general purposes of the study but considered all treatments as roughly equivalent. They belonged to the clinical staff and we have no reason to think that they should have had specific expectations about the outcomes of treatment in the different groups.
4) Please indicate if this study had a published, pre-specified protocol.

The study had not been pre-registered.
Nonetheless, the protocol had been declared and described at the beginning of the study and specified in the information sheets signed by the parents with informed consent.
More precisely, the experimental treatment protocol had been described by Bakker's group (the exact protocol is found in Bakker, 1990: Neuropsychological treatment of dyslexia. New York: Oxford University Press. The efficacy of the treatment, known as "hemisphere-specific stimulation", had been documented in peer-reviewed articles by Bakker and colleagues: Journal of Learning Disabilities 1990; Journal of Clinical Neuropsychology 1981; Journal of Clinical and Experimental Neuropsychology 1985). A published software had been used (Masutto & Fabbro, 1995. FlashWord: Training neuropsicologico per la dislessia. Gorizia: Ed. Tecnoscuola) and ad-hoc stimulus lists had been prepared and employed based on Bakker, 1990.
The protocols for Standard lateral, random lateral, central presentation and central fixed-time presentation were the same that were described in Lorusso et al., 2004. The protocol for control treatment was the same described as "RT group" in Lorusso et al. 2006 and, as specified in the paper, it was a traditional approach to dyslexia treatment; the therapists as a group had discussed and decided what materials and activities to use in the training.
The other groups were further manipulations of the VHSS programme newly designed for this study.

The assessment tools employed in the study are all published tests normed on the Italian population, with satisfactory validity and reliability values and widely used to assess reading and spelling abilities at the national level. Only the battery used for memory assessment (TEMA) was a published version of an English test (TOMAL, Reynolds and Biegler 1995).

1) **Outcome Data:** If possible, for each outcome measure, please provide the Standardized Mean Difference of Change between each group, for the main analyses comparing all treatment groups for P/L-type dyslexics, and for the main analyses comparing all treatment groups for M-type dyslexics

Formula for independent sample:
(T2-T1 means of group X) – (T2-T1 means of group Y)/(pooled standard deviation)

There were groups and no group was considered as a control group.
The groups were compared on three outcome measures: global reading accuracy, global reading speed and global spelling accuracy.
In the following tables, you find:

a) Descriptives of change-scores for each group (post-test minus pre-test) (NB dglobalaccuracy = mean accuracy change-score: dglobalspeed = mean speed change score: dglobaldictat = mean spelling change score; dglobalphon = global phonemic awareness change-score; dglobalmem = global memory change-score)
b) ANOVA on change-scores (to be consistent with the type of analysis that was run for the paper, I grouped data according to type of dyslexia, considering P and L-types as a single group and M-types as a second group)

T-tests for each pair of treatment groups, for the outcome measure that turned out to be significantly different between treatment groups, i.e. change in global spelling score

Ta ble 2. Res ults fo r all Glo bal Change Soores {rn z scores), in th e Diffe re nt Treatme nt Gro u ps, rn vided by Sub type

Type of Treaunenc	Dyslexia Subtype		Global Accuracy	Global Speed	Global Spelling	Global Phonemic Awareness	Global Memory
CONTR	P/L	*M*	0.57	1.08	1.65	- l.67	0.14
		SD	*J.37*	0.69	/.71	*1.33*	*0.54*
	M	*M*	OJS	2.55	0.26	- 2.17	0 .24
		SD	*2.86*	292	1.19	1.91	*0.30*
	Total	*M*	**0.46**	1.87	0.89	- l.92	0.19
		SD	2.2J	225	*1.55*	*1.59*	*0.41*
V-HSS	P/L	*M*	1.36	0.83	1.20	- 26 0	0.38
		SD	J. 16	*l.J 9*	/.76	2.27	*0.53*
	M	*M*	1.56	1.16	0.69	- 2.27	0.26
		SD	2.14	1.37	*1.54*	*2.34*	*0.41*
	Total	*M*	1.44	0.96	1.01	- 2.47	0.34
		SD	*J.59*	1.26	/.67	2.27	*0.49*
CP	P/L	*M*	1.23	**0.48**	1.81	---0.28	0.11
		SD	*0.55*	0.96	*1.58*	2.62	*0.45*
	M	*M*	1.38	1.70	2.63	- l.65	OJ J
		SD	2.1 *J*	*0.98*	2.26	2.28	*0.38*
	Total	*M*	1.32	1.20	2.30	- l.09	0.25
		SD	*J.63*	*l.J 3*	2.01	2.46	*0.41*
RLP	P/L	*M*	l. l l	0.73	---0.10	-1 .86	0.37
		SD	*J.07*	*1.09*	2.31	1.82	*0.64*
	M	*M*	1.4S	1.54	1.68	---0.90	---0.22
		SD	*J.38*	1.99	/.99	*2.34*	*0.35*
	Total	*M*	l.32	1.22	0.98	- l.29	0.06
		SD	*J.25*	1.70	2.24	2.14	*0.57*
CP-FT	P/L	*M*	**0.19**	1.71	1.42	- l. l<!	0.26
		SD	*J.08*	*l.OS*	/.7J	*1.07*	*0.42*
	M	*M*	1.78	2.19	0.59	- l.79	0.31
		SD	*J.28*	*3.49*	*0.83*	*0.95*	0.29
	Total	*M*	**0.93**	1.93	l.OJ	- l.46	0.29
		SD	*J.40*	2 41	*1.41*	*l.OJ*	0.36
R-HSS	P/L	*M*	0.27	1.10	0.44	---0.83	OAO
		SD	*0.80*	*0.59*	/. IJ	*1.48*	*0.44*
	Total	*M*	0.27	1.10	0.44	---0.83	OAO
		SD	*0.80*	*0.59*	*/. 13*	*1.48*	*0.44*
RH-stim	**M**	*M*	1.66	1.55	1.28	---0.8l	0.23
		SD	*J.8J*	*1.39*	*1.50*	*0.78*	0.46
	Total	*M*	1.66	1.55	1.28	---0.81	0.23
		SD	*J.8J*	*1.39*	*1.50*	*0.78*	*0.46*

Not" : CONTR = control grollir. V-HSS = standard lat.,ral P"" nmrion; RLP = random laa, ral P"'«entation: CP = c,,na-al P"" mation (mchtsto<co ie): CP-FT = central pr.,sent:ation. fixed rim"; R-HSS = r,,v.,rs<ad la ral prl×.,Jltatiol l; RH-<tim: <timulation of right hemsphere only.

Below, analyses for P-types and L-types only (typedicotom = 1)

Descrittivi[a]

		N	Media	Deviazione std.	Errore std.	Intervallo di confidenza 95% per la media		Minimo	Massimo
						Limite inferiore	Limite superiore		
dglobalaccuracy	control	6	,5733	1,36598	,55766	-,8602	2,0068	-,38	3,32
	HSS	20	1,3620	1,16337	,26014	,8175	1,9065	-,97	2,95
	central	9	1,2300	,54752	,18251	,8091	1,6509	,53	2,13
	random	7	1,1100	1,07022	,40450	,1202	2,0998	,25	3,03
	centrTFix	8	,1900	1,08283	,38284	-,7153	1,0953	-1,82	1,82
	reversed	9	,2722	,79519	,26506	-,3390	,8835	-,57	1,99
	Totale	59	,9066	1,10918	,14440	,6176	1,1957	-1,82	3,32
dglobalspeed	control	6	1,0817	,68770	,28075	,3600	1,8034	,40	2,01
	HSS	20	,8295	1,19486	,26718	,2703	1,3887	-2,58	2,78
	central	9	,4756	,95720	,31907	-,2602	1,2113	-1,16	1,65
	random	7	,7257	1,08798	,41122	-,2805	1,7319	-,95	2,12
	centrTFix	8	1,7138	1,05103	,37159	,8351	2,5924	,43	2,90
	reversed	9	1,1033	,59447	,19816	,6464	1,5603	-,02	1,83
	Totale	59	,9505	1,03502	,13475	,6808	1,2202	-2,58	2,90
dglobaldictat	control	5	1,6500	1,71165	,76547	-,4753	3,7753	-,40	3,61
	HSS	20	1,1965	1,75729	,39294	,3741	2,0189	-3,70	4,17
	central	9	1,8111	1,57715	,52572	,5988	3,0234	-,58	4,91
	random	7	-,1014	2,31176	,87376	-2,2395	2,0366	-3,76	2,11
	centrTFix	8	1,4213	1,73436	,61319	-,0287	2,8712	-2,10	4,24
	reversed	9	,4422	1,13430	,37810	-,4297	1,3141	-1,20	1,82
	Totale	58	1,0883	1,75105	,22992	,6279	1,5487	-3,76	4,91
dglobalphonol	control	6	-1,667	1,3292	,5426	-3,062	-,272	-3,5	,0
	HSS	20	-2,600	2,2746	,5086	-3,665	-1,535	-6,5	1,0
	central	9	-,278	2,6233	,8744	-2,294	1,739	-5,0	4,0
	random	7	-1,857	1,8192	,6876	-3,540	-,175	-4,5	1,0
	centrTFix	7	-1,143	1,0690	,4041	-2,132	-,154	-3,0	,5
	reversed	9	-,833	1,4790	,4930	-1,970	,304	-3,0	1,5
	Totale	58	-1,603	2,0917	,2746	-2,153	-1,053	-6,5	4,0
dglobalmemory	control	5	,1360	,54427	,24341	-,5398	,8118	-,73	,60
	HSS	20	,3755	,52599	,11762	,1293	,6217	-,47	1,41
	central	7	,1100	,44591	,16854	-,3024	,5224	-,77	,61
	random	7	,3657	,63880	,24144	-,2251	,9565	-,48	1,33
	centrTFix	8	,2625	,42026	,14859	-,0888	,6138	-,24	1,08
	reversed	9	,4022	,43694	,14565	,0664	,7381	-,33	1,07
	Totale	56	,3079	,49507	,06616	,1753	,4404	-,77	1,41

a. typedicotom = 1,00

ANOVA univariata[a]

		Somma dei quadrati	df	Media dei quadrati	F	Sig.
dglobalaccuracy	Fra gruppi	13,775	5	2,755	2,536	,039
	Entro gruppi	57,581	53	1,086		
	Totale	71,357	58			
dglobalspeed	Fra gruppi	7,651	5	1,530	1,488	,209
	Entro gruppi	54,482	53	1,028		
	Totale	62,133	58			
dglobaldictat	Fra gruppi	21,066	5	4,213	1,425	,231
	Entro gruppi	153,706	52	2,956		
	Totale	174,772	57			
dglobalphonol	Fra gruppi	42,976	5	8,595	2,165	,072
	Entro gruppi	206,403	52	3,969		
	Totale	249,379	57			
dglobalmemory	Fra gruppi	,633	5	,127	,493	,780
	Entro gruppi	12,847	50	,257		
	Totale	13,480	55			

a. typedicotom = 1,00

Post-hoc tests (for P- and L-types only, i.e. typedicotom = 1)

Confronti multipli[a]

Variabile dipendente: dglobalaccuracy
LSD

(I) type of treatment	(J) type of treatment	Differenza fra medie (I-J)	Errore std.	Sig.	Intervallo di confidenza 95%	
					Limite inferiore	Limite superiore
control	HSS	-,78867	,48518	,110	-1,7618	,1845
	central	-,65667	,54935	,237	-1,7585	,4452
	random	-,53667	,57990	,359	-1,6998	,6265
	centrTFix	,38333	,56292	,499	-,7457	1,5124
	reversed	,30111	,54935	,586	-,8008	1,4030
HSS	control	,78867	,48518	,110	-,1845	1,7618
	central	,13200	,41838	,754	-,7072	,9712
	random	,25200	,45774	,584	-,6661	1,1701
	centrTFix	1,17200*	,43604	,010	,2974	2,0466
	reversed	1,08978*	,41838	,012	,2506	1,9289
central	control	,65667	,54935	,237	-,4452	1,7585
	HSS	-,13200	,41838	,754	-,9712	,7072
	random	,12000	,52528	,820	-,9336	1,1736
	centrTFix	1,04000*	,50648	,045	,0241	2,0559
	reversed	,95778	,49136	,057	-,0278	1,9433
random	control	,53667	,57990	,359	-,6265	1,6998
	HSS	-,25200	,45774	,584	-1,1701	,6661
	central	-,12000	,52528	,820	-1,1736	,9336
	centrTFix	,92000	,53945	,094	-,1620	2,0020
	reversed	,83778	,52528	,117	-,2158	1,8914
centrTFix	control	-,38333	,56292	,499	-1,5124	,7457
	HSS	-1,17200*	,43604	,010	-2,0466	-,2974
	central	-1,04000*	,50648	,045	-2,0559	-,0241
	random	-,92000	,53945	,094	-2,0020	,1620
	reversed	-,08222	,50648	,872	-1,0981	,9336
reversed	control	-,30111	,54935	,586	-1,4030	,8008
	HSS	-1,08978*	,41838	,012	-1,9289	-,2506
	central	-,95778	,49136	,057	-1,9433	,0278
	random	-,83778	,52528	,117	-1,8914	,2158
	centrTFix	,08222	,50648	,872	-,9336	1,0981

*. La differenza media è significativa al livello 0.05

a. typedicotom = 1,00

Below, analyses for M-types (i.e. typedicotom = 3)

Descrittivi[a]

		N	Media	Deviazione std.	Errore std.	Intervallo di confidenza 95% per la media - Limite inferiore	Intervallo di confidenza 95% per la media - Limite superiore	Minimo	Massimo
dglobalaccuracy	control	7	,3543	2,85998	1,08097	-2,2908	2,9993	-2,69	5,89
	HSS	13	1,5646	2,14220	,59414	,2701	2,8591	-1,11	5,89
	central	13	1,3838	2,10771	,58457	,1102	2,6575	-,33	7,55
	random	11	1,4500	1,38387	,41725	,5203	2,3797	-,97	3,44
	centrTFix	7	1,7843	1,28272	,48482	,5980	2,9706	,72	4,33
	RHonly	13	1,6638	1,81210	,50259	,5688	2,7589	-,75	5,04
	Totale	64	1,4200	1,93478	,24185	,9367	1,9033	-2,69	7,55
dglobalspeed	control	7	2,5486	2,92540	1,10570	-,1570	5,2541	,36	8,88
	HSS	13	1,1615	1,37309	,38083	,3318	1,9913	-,91	4,22
	central	13	1,6969	,97914	,27157	1,1052	2,2886	,35	3,53
	random	11	1,5373	1,98566	,59870	,2033	2,8713	-2,05	4,46
	centrTFix	7	2,1871	3,48580	1,31751	-1,0367	5,4110	-,23	10,00
	RHonly	13	1,5469	1,39364	,38653	,7048	2,3891	,22	5,06
	Totale	64	1,6770	1,91962	,23995	1,1975	2,1565	-2,05	10,00
dglobaldictat	control	6	,2600	1,19055	,48604	-,9894	1,5094	-1,28	1,54
	HSS	12	,6908	1,53630	,44349	-,2853	1,6669	-2,92	3,49
	central	13	2,6323	2,26468	,62811	1,2638	4,0008	-,32	7,03
	random	11	1,6755	1,99084	,60026	,3380	3,0129	-,78	6,07
	centrTFix	7	,5929	,83408	,31525	-,1785	1,3643	-,47	2,05
	RHonly	13	1,2823	1,50354	,41701	,3737	2,1909	-1,60	4,00
	Totale	62	1,3439	1,83090	,23252	,8789	1,8088	-2,92	7,03
dglobalphonol	control	6	-2,167	1,9149	,7817	-4,176	-,157	-4,0	,0
	HSS	13	-2,269	2,3418	,6495	-3,684	-,854	-6,5	1,0
	central	13	-1,654	2,2766	,6314	-3,030	-,278	-7,0	1,5
	random	10	-,900	2,3428	,7409	-2,576	,776	-3,5	5,0
	centrTFix	7	-1,786	,9512	,3595	-2,665	-,906	-3,0	-,5
	RHonly	13	-,808	,7783	,2159	-1,278	-,337	-2,0	,5
	Totale	62	-1,548	1,9391	,2463	-2,041	-1,056	-7,0	5,0
dglobalmemory	control	6	,2417	,30314	,12376	-,0765	,5598	-,33	,47
	HSS	10	,2630	,41478	,13117	-,0337	,5597	-,66	,72
	central	13	,3254	,38453	,10665	,0930	,5578	-,32	1,01
	random	8	-,2163	,35161	,12431	-,5102	,0777	-,73	,34
	centrTFix	7	,3129	,29455	,11133	,0404	,5853	-,01	,88
	RHonly	13	,2315	,46271	,12833	-,0481	,5111	-,87	,82
	Totale	57	,2067	,41139	,05449	,0975	,3158	-,87	1,01

a. typedicotom = 3,00

ANOVA univariata[a]

		Somma dei quadrati	df	Media dei quadrati	F	Sig.
dglobalaccuracy	Fra gruppi	9,951	5	1,990	,511	,767
	Entro gruppi	225,882	58	3,895		
	Totale	235,833	63			
dglobalspeed	Fra gruppi	11,033	5	2,207	,579	,716
	Entro gruppi	221,117	58	3,812		
	Totale	232,150	63			
dglobaldictat	Fra gruppi	38,954	5	7,791	2,636	,033
	Entro gruppi	165,531	56	2,956		
	Totale	204,484	61			
dglobalphonol	Fra gruppi	20,924	5	4,185	1,124	,358
	Entro gruppi	208,431	56	3,722		
	Totale	229,355	61			
dglobalmemory	Fra gruppi	1,740	5	,348	2,294	,059
	Entro gruppi	7,737	51	,152		
	Totale	9,477	56			

a. typedicotom = 3,00

Post-hoc tests for global dictation (spelling) change-scores, for M-types only

Confronti multipli[a]

Variabile dipendente: dglobaldictat
LSD

(I) type of treatment	(J) type of treatment	Differenza fra medie (I-J)	Errore std.	Sig.	Intervallo di confidenza 95% Limite inferiore	Limite superiore
control	HSS	-,43083	,85964	,618	-2,1529	1,2912
	central	-2,37231*	,84854	,007	-4,0721	-,6725
	random	-1,41545	,87256	,110	-3,1634	,3325
	centrTFix	-,33286	,95652	,729	-2,2490	1,5833
	RHonly	-1,02231	,84854	,233	-2,7221	,6775
HSS	control	,43083	,85964	,618	-1,2912	2,1529
	central	-1,94147*	,68826	,007	-3,3202	-,5627
	random	-,98462	,71767	,176	-2,4223	,4530
	centrTFix	,09798	,81768	,905	-1,5400	1,7360
	RHonly	-,59147	,68826	,394	-1,9702	,7873
central	control	2,37231*	,84854	,007	,6725	4,0721
	HSS	1,94147*	,68826	,007	,5627	3,3202
	random	,95685	,70434	,180	-,4541	2,3678
	centrTFix	2,03945*	,80601	,014	,4248	3,6541
	RHonly	1,35000	,67435	,050	-,0009	2,7009
random	control	1,41545	,87256	,110	-,3325	3,1634
	HSS	,98462	,71767	,176	-,4530	2,4223
	central	-,95685	,70434	,180	-2,3678	,4541
	centrTFix	1,08260	,83126	,198	-,5826	2,7478
	RHonly	,39315	,70434	,579	-1,0178	1,8041
centrTFix	control	,33286	,95652	,729	-1,5833	2,2490
	HSS	-,09798	,81768	,905	-1,7360	1,5400
	central	-2,03945*	,80601	,014	-3,6541	-,4248
	random	-1,08260	,83126	,198	-2,7478	,5826
	RHonly	-,68945	,80601	,396	-2,3041	,9252
RHonly	control	1,02231	,84854	,233	-,6775	2,7221
	HSS	,59147	,68826	,394	-,7873	1,9702
	central	-1,35000	,67435	,050	-2,7009	,0009
	random	-,39315	,70434	,579	-1,8041	1,0178
	centrTFix	,68945	,80601	,396	-,9252	2,3041

*. La differenza media è significativa al livello 0.05

a. typedicotom = 3,00

In order to make results more generalizable, I add that the advantage of central presentation for global spelling improvement holds also when no distinction is made between dyslexia subtypes (N = 123), as shown in the table below:

LSD post-hoc test					
(I) type of treatment	(J) type of treatment	Differenza fra medie (I-J)	Errore std.	Sig.	Intervallo di confidenza 95%
central	control	1,40455*	,64625	,032	,1242
	HSS	1,28949*	,48468	,009	,3292
	random	1,31192*	,55620	,020	,2100
	centrTFix	1,26170*	,58599	,033	,1007
	reversed	1,85414*	,69246	,009	,4822
	RHonly	1,01406	,61221	,100	-,1988

2) **Age:** please provide the mean age and SD of all participants.

10,53 (1,835)

Table S17. *Additional study information*

Study Details	
Reference	Luniewska 2005 - Neither action nor phonological video games make dyslexic children read better
Corresponding Author	Katarzyna Jednorog (email: k.jednorog@nencki.gov.pl)

Quality Assessment - ROBINS

1) Please indicate if this study had a published, pre-specified protocol.

No, it had not.

Data Extraction

1) **Location:** Please indicate the location of where the interventions took place (e.g., school, hospital etc)

All testing sessions and the intervention meetings took place in the building of the Nencki Institute of Experimental Biology, Polish Academy of Sciences.

2) **Outcome Data:** If possible, for each outcome measure, comparing each group, please provide the Standardized Mean Difference of Change

Formula for independent sample:

(T2-T1 means of Experimental group) − (T2-T1 means of control group)/(pooled standard deviation)

Action video games (AVG – CON):
Word recognition: -0.53 (T2-T1 in CON: 2.33, AVG: 0.44)
Sentence reading: -0.03(T2-T1 in CON: 1.47, AVG: 1.31)
Decoding: 0.60 (T2-T1 in CON: -0.21, AVG: 3.11)

Phonological video games (PNAVG – CON):
Word recognition: -0.53 (T2-T1 in CON: 2.33, PNAVG: 0.07)
Sentence reading: -0.13 (T2-T1 in CON: 1.47, PNAVG: 0.89)
Decoding: 0.86 (T2-T1 in CON: -0.21, PNAVG: 3.26)

AVG vs PNAVG (AVG – PNAVG):
Word recognition: 0.08 (T2-T1 in AVG: 0.44, PNAVG: 0.07)
Sentence reading: 0.08 (T2-T1 in AVG: 1.31, PNAVG: 0.89)
Decoding: -0.03 (T2-T1 in AVG: 3.11, PNAVG: 3.26)

Word reading (words/minute): 0.27 (T2-T1 in AVG: 5.44, PNAVG: 3.67)
Word reading (inefficiency): -0.18 (T2-T1 in AVG: -17.05, PNAVG: -12.35)
Pseudoword reading (words/minute): -0.06 (T2-T1 in AVG: 4.19, PNAVG: 4.48)
Pseudoword reading (inefficiency): 0.10 (T2-T1 in AVG: -41.78, PNAVG: -48.71)

Vowel replacement: 0.00 (T2-T1 in AVG: 0.06, PNAVG: 0.06)
Phoneme deletion: -0.37 (T2-T1 in AVG: 0.01, PNAVG: 0.02)
Pseudoword repetition: -0.16 (T2-T1 in AVG: 0.03, PNAVG: 0.04)
Selective attention: -0.09 (T2-T1 in AVG: 0.14, PNAVG: 0.16)
RAN objects: 0.34 (T2-T1 in AVG: 0.08, PNAVG: 0.03)
RAN colours: 0.42 (T2-T1 in AVG: 0.05, PNAVG: -0.01)
RAN digits: 0.03 (T2-T1 in AVG: 0.05, PNAVG: 0.04)
RAN letters: 0.33 (T2-T1 in AVG: 0.11, PNAVG: 0.01)

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Appendix H – Chapter Four: Publication

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Flicker fusion thresholds as a clinical identifier of a magnocellular-deficit dyslexic subgroup

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The magnocellular-dorsal system is well isolated by high temporal frequency. However, temporal processing thresholds have seldom been explored in developmental dyslexia nor its subtypes. Hence, performances on two, four-alternative forced-choice achromatic flicker fusion threshold tasks modulated at low (5%) and high (75%) temporal contrast were compared in dyslexic and neurotypical children individually matched for age and intelligence (8–12 years, *n* = 54 per group). As expected, the higher modulation resulted in higher flicker fusion thresholds in both groups. Compared to neurotypicals, the dyslexic group displayed significantly lower ability to detect flicker at high temporal frequencies, both at low and high temporal contrast. Yet, discriminant analysis did not adequately distinguish the dyslexics from neurotypicals, on the basis of flicker thresholds alone. Rather, two distinct dyslexic subgroups were identified by cluster analysis – one characterised by significantly lower temporal frequency thresholds than neurotypicals (referred to as 'Magnocellular-Deficit' dyslexics; 53.7%), while the other group ('Magnocellular-Typical' dyslexics; 46.3%) had comparable thresholds to neurotypicals. The two dyslexic subgroups were not differentially associated with phonological or naming speed subtypes and showed comparable mean reading rate impairments. However, correlations between low modulation flicker fusion threshold and reading rate for the two subgroups were significantly different (*p* = .0009). Flicker fusion threshold performances also showed strong classification accuracy (79.3%) in dissociating the Magnocellular-Deficit dyslexics and neurotypicals. We propose that temporal visual processing impairments characterize a previously unidentified subgroup of dyslexia and suggest that measurement of flicker fusion thresholds could be used clinically to assist early diagnosis and appropriate treatment recommendations for dyslexia.

Abbreviations

FFT	Flicker fusion threshold
M	Magnocellular
P	Parvocellular
MD-Dyslexic	Magnocellular-deficit dyslexic
MT-Dyslexic	Magnocellular-typical dyslexic

Developmental Dyslexia is a heterogenous neurodevelopmental disorder affecting ~ 10% of individuals, who are characterized by impaired reading accuracy, speed and comprehension, i.e. dysfluency[1]. While dyslexia has most often been associated with impairments in phonological processing[2,3], the three most common models of dyslexia[4–6] propose several distinct subtypes. (1) A phonological deficit subtype also referred to as dysphonesia; (2) visually-based subtypes characterized by either an orthographic (i.e., dyseidesia or surface dyslexia[4,5]) or rapid naming speed deficit[6]; (3) combination subtypes with both phonological and orthographic deficits (referred to as dysphoneidesia or mixed dyslexia[4,5]) or both phonological and rapid naming deficits (referred

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to as a 'double-deficit'[6]); and (4) a 'no-deficit' subtype where those with dyslexia do not display phonological, orthographic or naming speed deficits despite significant reading difficulties.

Although less accepted, converging lines of evidence also implicate visual impairments in dyslexia across mechanisms specifically associated with the magnocellular (M) pathway of the retinocortical dorsal visual stream[7–16], with some suggesting that M-based impairments may only be experienced by a subgroup of dyslexic individuals[17]. However, the Magnocellular Theory of Dyslexia has remained somewhat contentious due to variability in findings and difficulty isolating the faster conducting M pathway that contributes to both the dorsal and ventral visual streams[18–23]. As yet, there is no well-established psychophysical measure of both spatial and temporal aspects of magnocellular-dorsal stream function that could be employed clinically to aid diagnosis of dyslexia and help guide appropriate interventions.

Indeed, temporal threshold manipulations, as compared to other proxies for M function properties such as low spatial frequency or low contrast performance have seldom been used to explore dyslexia. This is despite primate single cell physiological studies showing that the M stream is best isolated by stimuli presented at fast temporal frequencies[24–26], and evidence from Klistorner and colleagues[27] using multifocal Visually Evoked Potentials to show distinct temporally limiting stimulus recovery characteristics of the M and Parvocellular (P) pathway contributions to the primary visual cortex (V1) in humans (see also[28,29]). Where moving stimuli, such as in motion coherence tasks, have been used to study dyslexia, paradigms have usually been studied at frequencies well below the ~ 15 Hz needed to isolate M from P contributions in primates[26] and humans[11,30–32]. Moreover, the low contrast and spatial deficits often seen in dyslexic individuals have been reported to become more apparent at increasingly higher temporal frequencies[33,34], though only under certain conditions[35]. Hence, we propose that it may be the temporal processing properties of the magnocellular-dorsal system that is of greatest importance to reading, and that psychophysical tasks of temporal processing thresholds may prove to be the most valid and opportunistic, non-invasive tests of magnocellular sensitivity currently available.

The simplest test of temporal processing threshold for neural recovery to repeated stimulation is the Flicker Fusion Threshold (FFT) task which assesses the absolute temporal processing threshold at which rapid modulation of flickering light is no longer detectable– i.e., the point of fusion[36,37]. The high temporal and extremely low spatial properties of an achromatic FFT task means that the point of fusion is set by the speed of neural recovery of the faster M cells in the primary visual cortex[38,39]. Indeed, Brown and colleagues[28] demonstrated in neurotypical adults that temporal processing of achromatic low and high contrast FFTs correlate with M (but not P) nonlinear visual evoked potentials. The point of achromatic fusion is reported to occur between 35–64 Hz and is contingent on the luminance, size of lighting source and depth of modulation[36,37,40], and age[41,42]. FFTs have also been shown to be related to auditory temporal resolution and word decoding ability in typical readers[43,44], but to our knowledge, only five studies have compared the FFT performance, also referred to as critical flicker fusion, of individuals with dyslexia and typical readers[45–49]. Four of these studies found that on flicker fusion tasks using M-preferred stimuli, dyslexics displayed significantly lower temporal frequency thresholds (i.e., lower sensitivity) as compared to a typical reader group, but that FFTs for P-preferred tasks were not different where evaluated (see Supplementary Table S1 for a summary of each study).

Thus, the present study aimed to clarify the importance of rate of magnocellular processing for reading performance using FFTs, and to establish the utility of FFT tasks as a potential clinical measure of dyslexia, either in general or as a classifier of subtypes. Hence, we have compared the achromatic temporal processing thresholds of dyslexic children and neurotypical children (with normal reading skills), individually matched on age and nonverbal intelligence. The two achromatic FFT tasks modulated at high (75%) and low (5%) contrast were adopted from Brown and colleagues[28] and used as measures of the temporal frequency threshold (i.e., Hz) of M processing efficiency. Classification of dyslexic subtypes based on the presence and or absence of phonological awareness and rapid naming speed deficits (referred to as the Double-Deficit Hypothesis), was employed to identify if impairments in temporal processing of the visual system may be related to these previously proposed subtypes.

Specifically, the study aimed to explore the following research questions:

(i) Can FFT performance using low and high contrast achromatic FFT tasks dissociate groups of dyslexic and neurotypical children? And are there subgroups of dyslexic children with and without temporal processing (i.e., FFT) deficits?
(ii) If subgroups are present, are they associated with previously described subtypes of dyslexia?
(iii) Can FFT be used to discriminate dyslexic children with temporal deficits from neurotypical children and hence be established as a clinically useful test of magnocellular-dorsal functioning?

Results

Data analysis. An a priori power analysis indicated that with a total of 90 participants (e.g., 45 per group) there was 95% power to detect a moderate effect size at $p = .05$. Data screening of the complete dataset identified several outliers that were just outside the normal distribution. These outliers were treated using the Winsorization method, i.e., they were recoded to the largest value within the normal distribution to reduce the influence on parametric statistical analyses[50]. Normality was confirmed via assessment of skewness and kurtosis values, Shapiro–Wilk values, and visual inspection of histograms, Normal Q-Q plots and box plots. Cook distances were used to identify influential outlying data points in the correlational analyses; these data points were then removed from the relevant correlations. Preliminary analyses revealed no further violations of assumptions for the conducted analyses. Bonferroni adjustments were applied to the alpha level where multiple comparisons were conducted.

	Dyslexic children ($n = 54$)	Neurotypical children ($n = 54$)				
	M (SD)	*M (SD)*	*F*	*df*	*p*	*d*
Multivariate analysis	-	–	4.36	2, 105	.015*	0.50
75% FFT	48.18 (4.27)	50.41 (4.58)	6.93	1, 106	.010**	0.51
5% FFT	45.16 (4.52)	47.22 (3.62)	6.56	1, 106	.012*	0.50

Table 1. Comparison of flicker fusion thresholds in dyslexic and neurotypical children. Bonferroni adjusted alpha level of $*p < .016$, $**p \leq .01$; Cohen's $d \geq 0.2$, $d \geq 0.5$, and $d \geq 0.8$, represent small, medium, and large effect sizes, respectively.

Can differences in temporal processing dissociate groups of dyslexic and neurotypical children? Results of the multivariate analysis of variance show dyslexic children to have significantly lower flicker fusion sensitivity (i.e., slower temporal processing) at both 75% and 5% contrast as compared to the neurotypical children, both in the main multivariate analysis and subsequent univariate analyses, with moderate effect sizes (See Table 1).

Discriminant function analysis was used to identify whether FFTs could dissociate dyslexic children from neurotypicals. Results demonstrated that FFT sensitivity significantly differentiated dyslexic and neurotypical children, $\lambda = 0.923$, $\chi^2(2) = 8.367$, $p = 0.015$, $R^2 = 0.077$, with both the high contrast ($r = 0.888$) and low contrast tasks ($r = 0.863$) loading highly onto the discriminant function. However, the classification accuracy of the model was low. In total, 56.6% of dyslexic and 61.1% of neurotypical children were accurately classified. Overall, the model showed only a 58.9% classification accuracy. Thus, further analysis was conducted to identify if there were subgroups in the dyslexic sample.

Are there subgroups of dyslexic children with and without temporal processing deficits? Two-step cluster analysis based on the high and low contrast FFT performance of the dyslexic sample revealed a two-cluster solution. The analysis used a log-likelihood distance measure approach with Schwarz's Bayesian Criterion[51] and number of clusters were not specified in advance. The average silhouette measure = 0.60 (i.e., a measure of cluster cohesion and separation) indicated good cluster quality for the two clusters, as shown in Fig. 1 and Table 2. Subgroup A ($n = 29$; 53.7%) demonstrated FFT impairments and so were termed Magnocellular-Deficit Dyslexics (MD-Dyslexics), while Subgroup B ($n = 25$; 46.3%), who demonstrated unimpaired FFTs, were labelled Magnocellular-Typical Dyslexics (MT-Dyslexics). Overall, the low contrast (5% modulation) task was found to be the most discriminative predictor of cluster membership.

Results of the subsequent ANOVAs show the two dyslexic subgroups did not differ in age or nonverbal intelligence, nor text reading, phonological awareness nor rapid naming measures, confirming that the identified clusters were not an artifact of known factors (See Table 2). Rather, MD-Dyslexics were specifically characterized by significantly lower temporal thresholds (i.e., slower temporal processing) across FFT for both contrast modulation tasks compared with MT-Dyslexics and neurotypical children. In contrast, MT-Dyslexics demonstrated temporal thresholds that were equivalent to the neurotypical children at both contrast modulations, though their reading, rapid naming scores and phonological awareness were significantly reduced.

Are temporal processing deficits associated with previously described subtypes of dyslexia? The total dyslexic sample ($N = 54$) was classified into four subtypes based on performances at least 1 SD below age expectations on either the rapid naming composite (Naming Speed Deficit; $n = 12$), elision task (Phonological Deficit; $n = 10$), both tasks (Double-Deficit; $n = 18$), or neither task (No-Deficit; $n = 14$) according to criteria provided by Wolf and Bowers[6]. This permitted investigation to determine if these subtype classifications could predict those dyslexic participants identified with and without temporal processing impairments (i.e., FFT deficit) in the cluster analysis. Subtype classification was then confirmed via ANOVA (see Supplementary Information), and the presence (or absence) of a temporal processing deficit, based on the results of the cluster analysis, was entered as the dependent variable. The results of a direct logistic regression were not significant, χ^2 (3, $N = 54$) = 4.88, $p = 0.181$, indicating that temporal processing impairments per se are not specifically associated with the subtypes proposed by the Double-Deficit Hypothesis (See also Supplementary Table S2 and S3).

How do temporal visual processing thresholds relate to reading skills? As shown in Table 3, one-tailed Pearson correlational analyses revealed that better performance on the high contrast FFT task correlated significantly with better low contrast FFT, nonverbal intelligence, reading accuracy, reading rate, phonological awareness, and rapid naming performances in neurotypical children.

MD-Dyslexics showed a similar pattern of correlations, with high contrast FFT also correlating positively with low contrast FFT, reading accuracy, rate, phonological awareness and rapid naming performances, and low contrast FFT positively correlating with reading rate and phonological awareness. In the MT-Dyslexic subgroup, high and low contrast FFTs also positively correlated with phonological awareness, while low contrast FFT also correlated positively with nonverbal intelligence. Moreover, MT-Dyslexics, in contrast to MD-Dyslexics, showed a negative correlation between 5% FFT and reading rate. The difference in correlations between MT and MD subgroups, tested by applying Fisher's transformation between the groups for FFT 5% and reading rate, showed a significant difference ($Z = 3.33$, $p = 0.0009$, two-tailed).

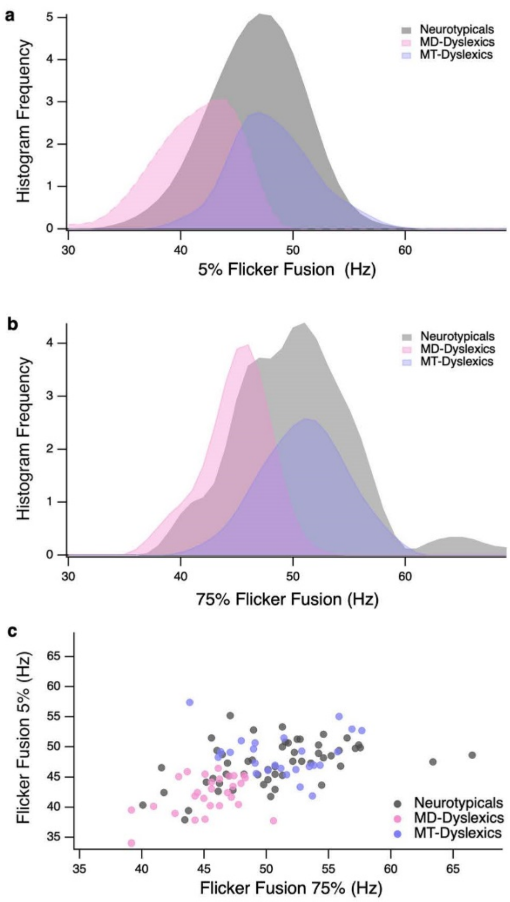

Figure 1. Flicker Fusion Threshold (FFT) distribution of the dyslexic subgroups identified via cluster analysis and of the Neurotypicals; Frequency distributions of Subgroup A ('Magnocellular-Deficit Dyslexics'), Subgroup B (Magnocellular-Typical Dyslexics') and Neurotypicals for (**a**) the Low Contrast (5%) FFT Task; and (**b**) the High Contrast (75%) FFT Task. (**c**) Scatterplot of Low and High Contrast FFT performance of the identified dyslexic clusters and neurotypicals. Note. Neurotypicals have been included in (**a**) and (**b**) for comparative purposes and were not included in the cluster analysis.

MT-Dyslexics also showed a negative trend in the relationship between FFTs and rapid naming. Scatterplots for phonological awareness, rapid naming, and reading rate are shown in Fig. 2. They indicate that the correlational differences reported between the two dyslexic subgroups are not due to difference in range of performances on phonological awareness, rapid naming and reading rate.

Is FFT a valid clinical identifier of dyslexic children with temporal deficits? Results of a second discriminant analysis showed that FFTs significantly differentiated the MD-Dyslexic subgroup from the neurotypical children, $\lambda = 0.631$, $\chi^2(2) = 36.411$, $p < 0.001$, canonical $R^2 = 0.370$, with both the high contrast ($r = 0.786$) and low contrast ($r = 0.916$) loading highly onto the discriminate function. Overall, the model showed strong classification accuracy (79.3%), with 82.14% (sensitivity) of MD-Dyslexics and 77.78% (specificity) of neurotypicals accurately classified.

Discussion

Thresholds of temporal processing have rarely been used to explore the Magnocellular Deficit Theory of Dyslexia, despite strong evidence indicating that the M stream is best isolated by its fast firing recovery rates, rather than just contrast and spatial properties[24–29]. Thus, the current study investigated temporal processing thresholds of

	a. MD-Dyslexics $n=29$		b. MT-Dyslexics $n=25$		c. Neurotypical children $n=54$					
	M (SD)	Range	*M (SD)*	range	*M (SD)*	range	F (2, 105)	p	d	Tukey HSD Post hoc
75% FFT	45.38 (2.66)	39.17–50.57	51.29 (3.54)	43.85–57.68	50.42 (4.57)	40.09–59.68	19.46	<.001	1.22	a<b**, a<c**, b=c
5% FFT	41.94 (3.23)	34.12–46.45	48.56 (3.31)	41.88–55.09	47.20 (3.64)	37.93–55.21	30.04	<.001	1.51	a<c**, a<c**, b=c
Age	9.96 (1.20)	8.00–12.25	10.34 (1.20)	8.08–12.92	9.86 (1.13)	8.00–12.17	1.46	.237	0.33	–
Nonverbal Intelligence	103.66 (8.87)	88–121	105.48 (6.96)	89–118	106.70 (10.19)	85–121	1.04	.357	0.28	–
Reading Accuracy	77.32 (9.15)	69–99	76.80 (6.27)	69–90	100.74 (10.25)	80–120	88.78	<.001	2.61	a<c**, b<c**, a=b
Reading Rate	74.56 (7.44)	69–90	76.44 (7.29)	69–90	99.96 (9.89)	80–124	103.96	<.001	2.84	a<c**, b<c**, a=b
Reading Comprehension	87.96 (14.45)	69–117	94.04 (12.50)	69–113	104.72 (11.80)	81–131	17.53	<.001	1.16	a<c**, b<c*, a=b
Phonological Awareness	87.81 (12.67)	70–116	87.20 (10.61)	70–110	103.33 (11.16)	85–125	25.34	<.001	1.40	a<c**, b<c**, a=b
Rapid Naming	82.78 (12.03)	61–104	84.00 (9.31)	69–104	95.26 (12.41)	69–118	13.59	<.001	1.04	a<c**, b<c**, a=b

Table 2. Comparison of neurotypical and dyslexic subgroups for flicker fusion, age, nonverbal intelligence, and reading measures. To account for the multiple comparisons, a Bonferroni adjustment to the alpha level ($p=.006$) was applied; Cohen's $d \geq 0.2$, $d \geq 0.5$, and $d \geq 0.8$, represent small, medium, and large effect sizes, respectively; FFT scores are reported in hertz; all neuropsychological measures are reported as Standard Scores. For post-hoc analyses *$p<.05$, ** $p<.001$.

	a. MD-Dyslexics $n=29$		b. MT-Dyslexics $n=25$		c. Neurotypicals $n=54$	
	5% FFT ($M=41.94$)	75% FFT ($M=45.38$)	5% FFT ($M=48.56$)	75% FFT ($M=51.29$)	5% FFT ($M=47.20$)	75% FFT ($M=50.42$)
5% FFT	–	.415*	–	.177	–	.498**
Nonverbal Intelligence	−.025	.161	.477**	.26	.162	.287*
Reading Accuracy	.182	.365*	.025	−.111	.122	.435**
Reading Rate	.343*	.337*	−.542**	.083	.053	.349**
Reading Comprehension	.278	−.158	.244	−.230	.092	.082
Phonological Awareness	.326*	.616**	.364*	.422*	.172	.429**
Rapid Naming	.313	.334*	−.313	−.304	.127	.284*

Table 3. Correlations between reading skills and flicker fusion thresholds for each group. *$p<.05$, ** $p<.01$; According to Cohen's guidelines, $r \geq 0.10$, $r \geq 0.30$, and $r \geq 0.50$, represent small, medium, and large effect sizes, respectively[68]; standard scores are used for all clinical tasks. FFTs are reported in Hz.

dyslexic and typical children using FFTs, at both low and high contrast, to comprehensively establish a magnocellular-temporo-spatial test that could be utilized clinically.

Our findings extend on those from previous FFT studies of dyslexia[45–48] by showing significant heterogeneity in dyslexic FFT performances and, more importantly, establishing the presence of two distinct subgroups – one characterized by impaired magnocellular-temporal processing thresholds (MD-Dyslexics) and the other by threshold levels equivalent to those of neurotypicals (MT-Dyslexics). The finding that 53.7% of the dyslexic sample were classified as MD-Dyslexics is comparable with the prevalence reported for phonological (47–62%) and rapid naming (19–44%) subtypes of dyslexia[52]. Although no previous FFT study has analysed the presence of dyslexic subgroups with and without temporal deficits, research from our lab has shown that 43–50% of dyslexic children demonstrated FFTs 1 SD below matched controls[45]. Similarly, McLean, et al. [48] identified that 42.5% of their dyslexic children performed 1 SD below matched controls on M-based temporal thresholds. Together, the consistency of these findings suggests that almost half of dyslexic individuals are likely to be characterised by magnocellular-temporal processing impairments.

Our results indicate that the presence of temporal processing impairments are not necessarily related to the phonological, rapid naming, double-deficit, or no-deficit subtypes of dyslexia that are proposed by Wolf and Bowers' Double-Deficit Hypothesis[6] and so provide evidence for the identification of a new subgroup of dyslexia characterised by visual temporal processing differences. Our results compliment the findings of several studies showing little association between tests of M functioning and specific subtypes of dyslexia[53,54], however, others studies have reported a link between M functioning and phonological and double-deficit subtypes[55–58], indicating a clear need for further research. Inclusion of orthographic processing tasks, for example, would enable future FFT research to further explore dyseidetic and surface subtypes[4,5].

The MD-Dyslexic and neurotypical groups showed similar correlation patterns. FFT performance, particularly high contrast FFT, was related to performance in almost all reading measures assessed (reading accuracy and rate, phonological awareness, rapid naming, but not reading comprehension). By comparison, the FFTs of MT-Dyslexics showed a different relationship pattern with reading skills: 5% contrast FFT was negatively related to

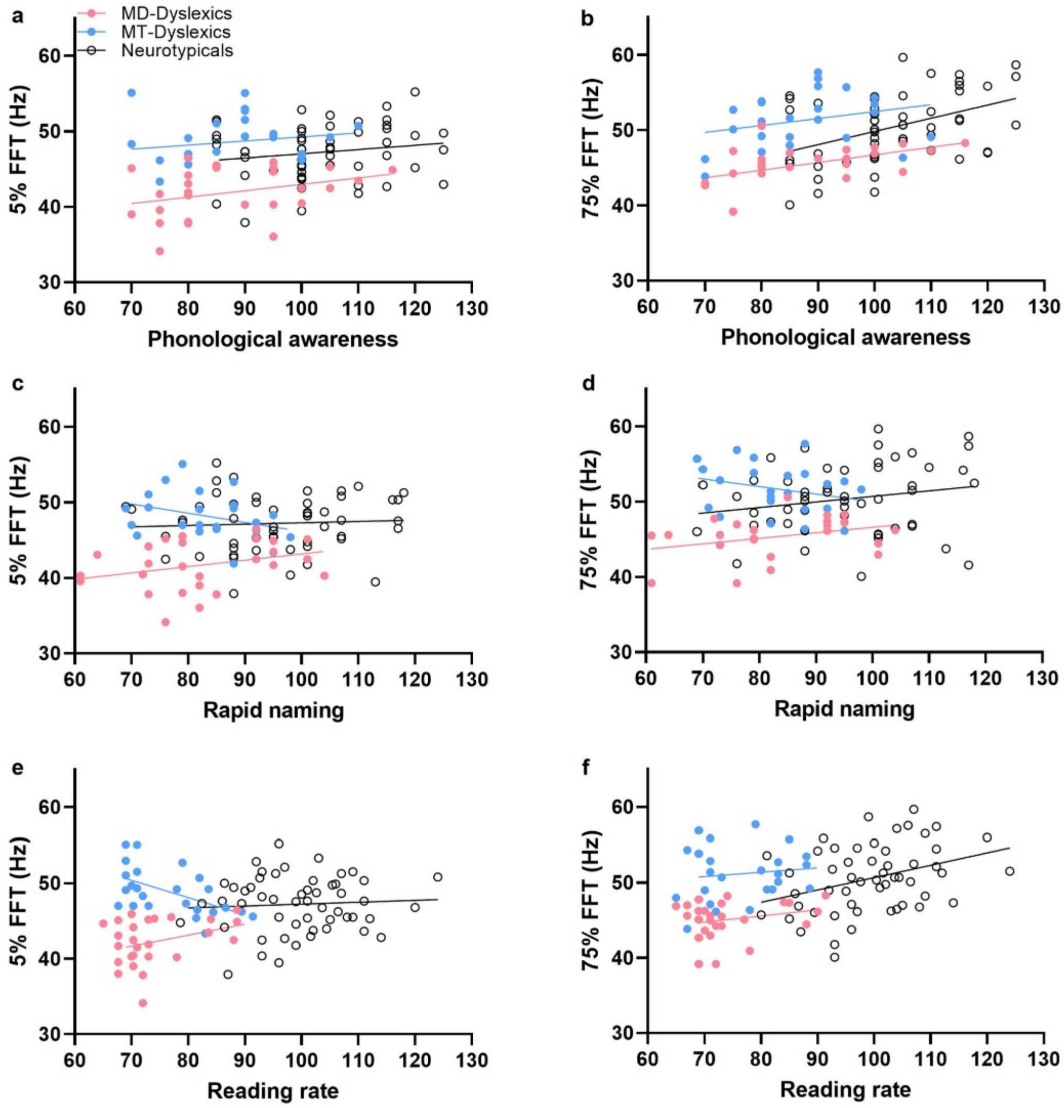

Figure 2. Correlations between Flicker Fusion Thresholds (FFTs) and reading measures; Low Contrast (5%) FFTs and (**a**) Phonological awareness; (**c**) Rapid Naming; (**d**) Reading Rate; and High Contrast (75%) FFTs with (**b**) Phonological awareness; (**d**) Rapid naming; (**f**) Reading rate.

reading rate (i.e., speed); there were also non-significant negative trends between FFTs and rapid naming, a task also reliant on speed. However, like the other two groups, FFTs of the MT-Dyslexics correlated with phonological awareness. This is consistent with several other papers that show a relationship between M functioning and phonological skills[44,46,59–62]. While it is not fully clear what other factors differentially characterise MD-Dyslexics and MT-Dyslexics, several possibilities can be speculated from the current findings. Reading rate and low contrast temporal processing were positively related in MD-Dyslexics, but negatively related in MT-Dyslexics. This dissociation was statistically significant and provides novel evidence indicative of a relationship between temporal processing speed and reading speed. For MT-Dyslexics, despite efficient temporal processing speed, performance on speed-based measures (i.e., reading rate and naming speed) are likely to be related to additional factors not measured in the current study, such as speed of articulation, automaticity in accessing the multiple cognitive processes required by both tasks, and other cognitive processes, including working memory.

	Dyslexic children (N = 54)			Neurotypical children (N = 54)					
	M	SD	$Range$	M	SD	Range	t (106)	p	d
Age	10.14	1.20	8.00–12.92	9.86	1.13	8.00–12.17	− 1.25	.219	0.24
Nonverbal intelligence	104.50	8.02	88–121	106.70	10.19	85–121	1.5	.215	− 0.24
Reading Accuracy	77.08	7.85	69–99	100.74	10.25	80–120	13.38	< .001**	− 2.59
Reading Rate	76.00	8.71	69–103	99.96	9.89	80–124	13.22	< .001**	− 2.57
Reading Comprehension	91.53	15.28	69–131	104.72	11.79	81–131	5.01	< .001**	− 0.97
Phonological Awareness	87.52	11.61	70–116	103.33	11.16	85–125	7.15	< .001**	− 1.39
Rapid Naming	83.14	11.14	58–104	95.26	12.41	69–118	5.24	< .001**	− 1.03

Table 4. Descriptives and comparisons of dyslexic and neurotypical children. All scores, except for age, are reported as standard scores; Cohen's $d \geq 0.2$, $d \geq 0.5$, and $d \geq 0.8$, represent small, medium, and large effect sizes, respectively.

In the current study, MD-Dyslexics demonstrated flicker frequency thresholds that were on average 10–13% (~ 5 to 6 Hz) lower than MT-Dyslexics and neurotypicals (as shown in Table 2). Reduced FFT performance can be used to discriminate MD-Dyslexics from neurotypical populations with good sensitivity (82.14%) and specificity (77.78%). Although the clinical significance of a specific M-based temporo-spatial psychophysical task has rarely been considered in past research, similar classification accuracy was reported for adult dyslexics by Talcott[46], as shown in Supplementary Table S1. Our results provide initial evidence for the clinical applicability of FFT tasks as reliable measures of magnocellular-temporal efficiency that could be used to aid assessment and diagnosis of one subgroup of dyslexia. As interventions that target other properties of the M stream (i.e., motion and contrast) show strong efficacy in improving aspects of reading, and in particular reading rate[63,64], future research should also consider evaluating the utility of FFT and other temporal processing training programs for dyslexia.

In summary, the findings of the current study establish that a subgroup of dyslexic children (MD-Dyslexics) are specifically characterized by a significant impairment in magnocellular-temporal processing thresholds. The presence of this temporal impairment was not better categorized by the presence or absence of phonological awareness and/or rapid naming impairments as is commonly used to classify dyslexic subtypes in past research. It was also not an artifact of differences in age, nonverbal intelligence, nor severity or pattern of reading impairments between the MD-Dyslexic and MT-Dyslexic subgroups as they were comparable on reading, phonological awareness and rapid naming performances. Rather, for MD-Dyslexics, poorer FFTs, particularly high contrast FFT, was related to worse reading accuracy, reading rate, phonological awareness and rapid naming outcomes. In contrast, the FFTs of MT-Dyslexics were much less related to reading outcomes. Thus, we propose that temporal processing impairments characterize a previously unidentified subtype of dyslexia. This subtype can be easily identified using FFT tasks with good clinical accuracy (79.3%). FFTs tasks should therefore be considered as a valid non-invasive test of magnocellular temporal efficiency for dyslexia, that could be clinically used to assist diagnosis and appropriate treatment recommendations. FFT tasks could also prove useful in identifying pre-reading children at risk of developing dyslexia, though further research is required.

Methods

Participants and procedure. A total of 58 dyslexic children and 70 neurotypical children with normal reading ability between the ages of 8–12 years, from Grades 3–6, participated in the study. Of those, 54 dyslexics and 54 neurotypicals were able to be one-to-one matched within ± 0.73 SD of nonverbal intelligence, and within ± 1 year of age, and these 108 children were included in the analyses (See Table 4 for descriptives and group comparisons).

Participants were recruited and assessed at Melbourne metropolitan primary schools and an extra-curricular summer education program for those with reading difficulties between 2017 and 2018. All participants had normal intelligence (Standard score ≥ 85 for age on the Raven's Coloured Progressive Matrices test), normal or corrected-to-normal vision and hearing, and English as their primary language. Children with known medical and neurodevelopmental disorders other than dyslexia (e.g., ASD, ADHD) were excluded. To be included in the dyslexic sample, participants required (1) a history of reading difficulties as reported by teachers or parents and/or a formal diagnosis of dyslexia, and (2) reading performance at least 1.25 SD[52] below age-standardized norms in one or more area of reading (text reading accuracy, rate and/or comprehension) on the York Assessment of Reading for Comprehension—Primary Reading (YARC[65]), as confirmed by a psychologist on the research team. Parents of participants provided written informed consent for their child to engage in the study and all children who participated provided verbal assent. Testing occurred in a quiet, light-controlled room either at the child's school or at the site of the educational program, with tasks administered in randomized order. The experiment was performed in accordance with relevant guidelines and regulations and with ethics approval granted by the La Trobe University Faculty Human Ethics Committee and the Victorian State Department of Education.

Materials

Neuropsychological tests. Nonverbal intelligence was assessed using the Raven's Coloured Progressive Matrices[66]. The YARC was used to assess text reading accuracy, rate and comprehension skills[65]. The elision subtest, a measure of phonological awareness, and the rapid symbolic naming composite, consisting of letter and number rapid naming tasks, from the Comprehensive Test of Phonological Processing, 2nd Edition[67] (CTOPP-2) were administered to investigate relationships between FFT and reading-related skills and to classify dyslexic participants into subtypes as based on the Double-Deficit Hypothesis[6]. All psychometric measures are reported as standardized scores obtained from the norm referenced instruments.

Temporal processing thresholds. Two achromatic FFT tasks, modulated at high (75%) and low (5%) contrast in separate experimental tasks, were used. Four LEDs (A-Bright Industrial Co., China, part AL-513W3c-003 white) conveyed light into separate 6 mm diameter optic fibre light guides which were presented flush in a free-standing wooden panel in a diamond-array subtending 1.0º, center-to-center, at the eye. The task was designed with VPixx software and flicker modulation was controlled via a DATAPixx device (10 kHz sampling allowed for smooth temporally modulated sinusoidal waveforms with frequencies in excess of 100 Hz). A gaussian temporal envelope (Full width at half maximum = 480 ms) was used to smooth the onset and offset of the flicker to prevent the alerting of change sensitive mechanisms and each light was calibrated for luminance. Each task consisted of a four-alternative forced-choice deign with 32 trials and used a Parameter Estimation by Sequential Testing. For further details about task design, see Brown[28].

Participants completed the task at a viewing distance of 60 cm in a dimly lit room. They were instructed that one LED light per trial (demarcated by a high-pitched beep) would flicker for 3 s and at the end of the trial (indicated by a low-pitched beep) they were required to indicate which light source they saw flicker or guess when they were unsure. Prior to task commencement, participants were provided a practice session to familiarize them. During the tasks, the start of each trial was manually controlled by the experimenter to ensure participants were attending, and the onset of a trial began with a high pitch beep and finished with a low pitch. The order of high and low contrast conditions was counterbalanced to control for practice effects.

Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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Author contributions
J.P., E.B. and S.C. designed the experiment, and E.B. and S.C. supervised the project. D.C. built the psychophysical task. J.P. and A.B. performed the experiment. J.P. analysed data and wrote the manuscript, with all other authors contributing to the drafting of the manuscript. All authors reviewed the manuscript.

Competing interests
The authors declare no competing interests.

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Appendix I – Chapter Four: Supplementary Information

Supplementary Information

Flicker Fusion Thresholds as a Clinical Identifier of a Magnocellular-Deficit Dyslexic Subgroup

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Supplementary Table S1.
Studies Comparing Flicker Fusion Thresholds in Dyslexic and Typical Readers

Citation	Participants *N*	Age M (SD), Range	Task Description	Results
Chase and Jenner (1993)	7 dyslexics; 8 typical readers	17-22	Visual temporal processing thresholds assessed using 4 trials of paired visual stimuli presented spatiotemporally to result in a 'fused' overlapping composite image at threshold. Participants indicated when the display no longer appeared to flicker. Magnocellular conditions: Shape, apparent movement, letters. Parvocellular condition: equiluminant red/green colour.	Across groups, flicker fusion thresholds for magnocellular tasks were faster than parvocellular tasks (31.9 Hz versus 16.7 Hz, respectively). Magnocellular condition: Flicker Fusion thresholds were significantly lower in dyslexics (M = 26.1 Hz) as compared to controls (M = 38.4 Hz) Parvocellular condition: No differences between dyslexics and controls (~15.87 Hz versus ~17.24 Hz, respectively, as estimated from figure)
Talcott et al. (1998)	18 dyslexics; 18 typical readers Matched for age and intelligence	dyslexics M = 27.6, 18-41; typical readers M = 24.5, 19-34	Magnocellular visual temporal processing thresholds assessed using 2AFC 100% luminance contrast achromatic LED FFT task	Flicker Fusion thresholds were significantly lower in dyslexics (M = 52.8 Hz, SD = 0.87 Hz) as compared to controls (M = 57.1 Hz, SD = 1.18 Hz) Combined performance on Flicker Fusion thresholds and motion coherence demonstrated 72.2% sensitivity and 83.3% specificity in discriminating dyslexic adults from controls.
(Edwards et al., 2004)	21 dyslexics; 24 typical readers	dyslexics M = 11.17 (1.08); typical readers M = 11.62 (1.49)	Magnocellular visual temporal processing thresholds assessed using a red LED chromatic flicker perception task, with separate experimental runs at high (100%) and low (10%) luminance contrast. Participants indicated when the light stopped or started flickering.	Low Contrast (10%) Flicker Fusion thresholds were not significantly lower in dyslexics (M = 24.44 Hz, SD = 5.91 Hz) as compared to controls (M = 23.57 Hz, SD = 2.97 Hz) High Contrast (100%) Flicker Fusion thresholds were not significantly lower in dyslexics (M = 36.61 Hz, SD = 3.92 Hz) as compared to controls (M = 37.04 Hz, SD = 2.31 Hz)
McLean, Stuart, Coltheart, and Castles (2011)	40 dyslexics; 42 typical readers	dyslexics M = 9.5 (1.4); typical readers M = 9.6 (1.3)	Visual temporal processing thresholds assessed using a two-color red/green LED chromatic flicker perception task. Participants indicated when the light stopped or started flickering. Parvocellular condition: The frequency at which red/green color differentials were no longer discernable (i.e., 'fused' to a stable orange colour). Magnocellular condition: The magnocellular temporal threshold for isoluminant color flicker was recorded as the flicker frequency at which participants could no longer detect any flicker.	Parvocellular condition: No differences between dyslexics (20.63 Hz) and controls (21.23 Hz) Magnocellular condition: Flicker Fusion thresholds were significantly lower in dyslexics (29.480 Hz) as compared to controls (30.838 Hz)

Brown, Peters, Parsons, Crewther, and Crewther (2020)	18 dyslexics; 18 typical readers Matched for age and intelligence	dyslexics M = 10;04 (1;03); typical readers M = 10;06 (1;04)	Magnocellular visual temporal processing thresholds assessed using two 4AFC achromatic LED FFT tasks at 75% and 5% luminance contrast	Low Contrast (5%) Flicker Fusion thresholds were significantly lower in dyslexics (M = 44.23 Hz, SD = 4.86 Hz) as compared to controls (M = 47.15 Hz, SD = 3.22 Hz) High Contrast (75%) Flicker Fusion thresholds were significantly lower in dyslexics (M = 47.64 Hz, SD = 3.62 Hz) as compared to controls (M = 51.04 Hz, SD = 4.08 Hz)

Supplementary Results:

Subgroup Characteristics: Identified Subgroups are not related to Double-Deficit Hypothesis Subtypes

The dyslexic sample were grouped into four subtypes according to the Double-Deficit Hypothesis to identify if subtypes predicted whether or not a dyslexic participant would have temporal processing impairments as based on the identified clusters. Participants were classified into the four subtypes based on whether they performed ≥1 SD below **age-standardized norms on either rapid naming, phonological awareness, both tasks, or neither task.** An ANOVA confirmed that the subtypes differed in accordance with the Double-Deficit Hypothesis (see Table S1). Results show that the Naming Speed Deficit and Double-Deficit subtypes had significantly poorer rapid naming performance than the Phonological and No Deficit Subtypes. As expected, the Naming Speed Deficit and Double-Deficit subtypes had comparable rapid naming performance. In comparison, the Phonological and Double-Deficit subtypes had significantly poorer phonological awareness performance than the Naming Speed Deficit and No Deficit Subtypes but performed comparably to each other. The groups also did not differ in age, nonverbal intelligence, reading rate or reading comprehension, but there were differences in reading accuracy, with the no-deficit subtypes performing significantly better than the other subtypes (See Supplementary Table S2).

To identify if the two clusters of dyslexics were associated with specific subtypes of DD, a logistic regression was performed. The presence (or absence) of a temporal processing deficit as based on the results of the cluster analysis was entered as the dependent variable, and the four subtypes (Phonological Deficit, Naming Speed Deficit, Double-Deficit, and No-Deficit) were entered as independent categorical predictors. The No Deficit Subtype was removed from the final model due to collinearity. The results of a direct logistic regression were not significant, χ^2 (3, N = 54) = 4.88, p = .181, indicating that temporal processing impairments are not associated with specific subtypes. The model explained between 8.60% (Cox & Snell R^2) and 11.50% (Nagelkerke R^2) of the variance in temporal processing status, and correctly identified 64.80% of cases. As shown in Supplementary Table S3, none of the independent variables made a unique statistically significant contribution to the model.

Supplementary Table S2.

Univariate analyses comparing dyslexic subtypes on phonological and rapid naming performances, nonverbal intelligence, age, and reading performances

	Subtypes Phonological Deficit (PD) *n* = 10	Naming Speed Deficit (NSD) *n* = 12	Double-Deficit (DD) *n* = 18	No-Deficit (ND) *n* = 14				
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	F (3, 53)	p	d	Tukey HSD Post hoc
Rapid Naming	93.44 (4.87)	74.91 (8.54)	76.06 (6.37)	94.25 (5.83)	31.60	<.001	0.78	NSD<PD**, NSD<ND**, NSD=DD, DD<PD**, DD<ND**, PD=ND
Phon. Awareness	77.00 (5.87)	94.54 (4.16)	79.17 (3.93)	101.23 (8.09)	55.89	<.001	0.67	PD<NSD**, PD<ND**, PD=DD, NSD=ND, DD<NSD**, DD<ND**
Age	10.71 (1.43)	9.92 (1.10)	10.35 (1.08)	9.63 (1.13)	2.02	.122	0.69	
NVIQ	101.30 (5.27)	104.33 (8.94)	106.17 (9.07)	104.78 (7.48)	0.78	.507	0.43	
Reading Accuracy	75.20 (5.73)	76.75 (6.35)	73.11 (5.19)	84.31 (9.18)	7.39	<.001	1.34	ND>PD*, ND>NSD*, ND>DD**, PD=NSD, PD=DD, NSD=DD
Reading Rate	77.80 (10.79)	73.91 (6.79)	73.28 (6.64)	80.15 (9.90)	2.04	.121	0.71	
Reading Comprehension	92.30 (15.02)	91.42 (22.72)	90.17 (12.90)	92.92 (11.31)	0.08	.967	0.14	

Note. *$p < .05$, ** $p < .001$; Cohen's $d \geq 0.2$, $d \geq 0.5$, and $d \geq 0.8$, represent small, medium, and large effect sizes, respectively; all neuropsychological measures are reported as Standard Scores.

Supplementary Table S3.
Logistic Regression Predicting Likelihood of a Temporal Processing Impairment from Double-Deficit Hypothesis Subtypes

Dyslexic Subtypes	B	S.E	Wald	*df*	*p*	Odds Ratio	95.0% C.I for Odds Ratio Lower	Upper
Naming Speed Deficit	-0.92	.81	1.31	1	.253	0.39	0.08	1.94
Phonological Deficit	-1.44	.89	2.62	1	.106	0.24	0.04	1.36
Double-Deficit	0.11	.75	0.02	1	.888	1.11	0.26	4.82
No-Deficit	-	-	-	-	-	-	-	-
Constant	0.59	.56	1.11	1	.292	1.80		

Note: The No Deficit Subtype was automatically removed from the regression model due to collinearity.

Table S4.
Regression Equations and R^2 values for Correlations between Flicker Fusion Thresholds (FFTs) and Reading Measures in Each Group (As Shown in Figure 2).

	Phonological Awareness	Rapid Naming	Reading Rate
Low Contrast (5%) Flicker Fusion Thresholds			
MD-Dyslexics	Y = 0.08512*X + 34.46; R^2 = 0.1064	Y = 0.08393*X + 34.77; R^2 = 0.09812	Y = 0.1461*X + 31.43; R^2 = 0.1173
MT-Dyslexics	Y = 0.05420*X + 43.83; R^2 = 0.03021	Y = -0.1214*X + 58.28; R^2 = 0.1095	Y = -0.2285*X + 66.38; R^2 = 0.2940
Neurotypicals	Y = 0.05620*X + 41.40; R^2 = 0.02972	Y = 0.01783*X+ 45.50; R^2 = 0.003633	Y = 0.02502*X + 44.73; R^2 = 0.004145
High Contrast (75%) Flicker Fusion Thresholds			
MD-Dyslexics	Y = 0.1017*X + 36.54; R^2 = 0.2597	Y = 0.07337*X + 39.27; R^2 = 0.1118	Y = 0.08191*X + 39.01; R^2 = 0.05548
MT-Dyslexics	Y = 0.09221*X + 43.25; R^2 = 0.07648	Y = -0.1012*X + 60.12; R^2 = 0.06831	Y = 0.05778*X + 46.75; R^2 = 0.01381
Neurotypicals	Y = 0.1754*X + 32.29; R^2 = 0.1838)	Y = 0.07383*X + 43.33; R^2 = 0.03990	Y = 0.1640*X + 34.26; R^2 = 0.1218

Appendix J – Chapter Five: Publication

frontiers in Human Neuroscience

ORIGINAL RESEARCH
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Eye Movements During RAN as an Operationalization of the RAN-Reading "Microcosm"

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Rapid Automatized Naming (RAN) is a strong predictor of reading aloud, though there is little agreement on what underpins RAN or how it relates to reading. Some theorize phonological skills, while others suggest that RAN reflects the "microcosm" of cognitive and attentional processes also required for reading, with more recent research using eye movements in an attempt to study this relationship. In the current study, we aimed to extend previous investigations to identify whether the temporal patterns of eye movements predict RAN and can, therefore, be established as a method to study the cognitive processes underlying RAN that could then be utilized to elucidate the relationship of RAN to reading. A Gazepoint eye tracker was used to record the eye movements of 93 learner readers aged 5–8 years (*M* age = 7.00) while performing a custom computerized alphabetic RAN task. Text reading accuracy, comprehension and rate; nonverbal intelligence; and phonological awareness abilities were also assessed. Regression analyses showed that, independently of phonological awareness, eye movements [Fixation Count (FC) and Fixation Duration (FD)] measured during RAN tasks were highly reflective of children's rapid naming performance (92.8%). Both mean FC and mean FD during RAN tasks also predicted text reading accuracy (36.3%), comprehension (31.6%), and rate (36.2%) scores, and in predicting these text reading skills there was a high level of shared variance with RAN performance. In a sub-sample of participants, longer average FDs and counts independently discriminated children with reading difficulties (*n* = 18; aged 7–9) from neurotypical children matched for age (*n* = 18), but not from younger neurotypical children matched for reading level (*n* = 18; aged 5–6). Together, these results suggest that the analysis of eye movements recorded during RAN allows for the operationalization of many of the spatially and temporally-bound cognitive and attentional processes that underpin the RAN, and a step towards elucidating its relationship to reading.

Keywords: eye movements, rapid naming, reading, dyslexia, young children, ocular motor patterns, microcosm

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INTRODUCTION

Rapid Automatic Naming (RAN) is commonly used to measure the ability to rapidly, accurately, and sequentially name a series of repetitive and familiar visual stimuli (i.e., pictures, colors, letters or digits; Denckla and Rudel, 1974). RAN tasks are also known to successfully differentiate those individuals with and those without diagnosed reading difficulties (i.e., specific learning disorder in reading, developmental dyslexia; Denckla and Rudel, 1974). However, until the last few years, there has been little consensus about how RAN relates to reading (for a review, see Kirby et al., 2010), Indeed, early interpretation of the RAN-reading relationship was associated with an impaired ability to make adequate visual to verbal conversions (letter-sound conversions) during RAN and reading, thus limiting the automaticity of access to the phonological representation and impairing task performance (Torgesen et al., 1997; Clarke et al., 2005; Vukovic and Siegel, 2006; Savage et al., 2007; Ziegler et al., 2010). A second common interpretation has been that RAN reflects more a microcosm of the multiple cognitive and attentional skills required for reading (Denckla, 1988), which must take place in the context of sequentially organized eye movements. Recent studies have attempted to elucidate these hypotheses by investigating the individual differences in eye movements as a means to identify which cognitive processes may contribute to RAN (Jones et al., 2008, 2010, 2013; Pan et al., 2013; Yan et al., 2013; Al Dahhan et al., 2014, 2017). However, whether eye movements during RAN are reflective of, and hence predictive of overall RAN performance has not yet been fully elucidated. If indeed the eye movement characteristics are not strong predictors, then using gaze technology to study cognitive processing during RAN would be theoretically uninformative. Thus, the current study aimed to first establish whether RAN performance is dependent on the mean duration and number of fixations needed to name each RAN stimuli, which should lead to confirmation that eye movements can be used to operationalize and measure the time needed to accomplish the cognitive and attentional processes that underpin RAN. Such understanding of the time constraints needed for successful familiar object recognition and verbalization during RAN will add information to how RAN is related to reading fluency and why those with reading difficulties often perform poorly on RAN tasks.

Much of the earliest work relating to eye movements and cognitive demands in tasks related to reading was pioneered by Rayner (1998). For example, fixations are longer and saccade sizes are shorter during oral reading as compared to silent reading (Rayner, 1998; Kim et al., 2019), while saccades, regressions, and Fixation Durations (FDs) increase with greater visual/orthographic similarity during RAN (Al Dahhan et al., 2017). Recent research has also shown that individual differences in temporally-based *fixation durations* are indicative of duration of attentional engagement related to speed of visual, symbolic, and orthographic processing and potentially include time to access the lexicon and verbalize the stimuli (Eckstein et al., 2017; Kim et al., 2019). *Mean fixation counts* per stimuli have been suggested to measure spatial distribution of attention indicative of the amount of visual information processed in each fixation (Goldberg and Kotval, 1999; Holland and Komogortsev, 2011; Rayner et al., 2013), while *saccade duration*, a measure dependent on speed of activation and time to move to the spatial location of the next stimuli to be attended (Baloh et al., 1975), may provide insights into the cognitive processes that take place between fixations during RAN and reading. Neural networks associated with eye movement control and attention are similarly activated in both RAN and reading (i.e., the "reading network"; Misra et al., 2004), leading to the suggestion that RAN could be considered as a surrogate measure of the efficiency of this "reading network" (Al Dahhan et al., 2016), and that eye movements could provide insight into the cognitive and attentional processes important to both RAN and reading.

Furthermore, children and adults diagnosed with a reading disorder are consistently reported to display less efficient patterns of eye movements during RAN and reading tasks, i.e., smaller perceptual spans, longer and more fixations per word, shorter saccades, and more regressions when compared with age-matched typical readers (Rayner, 1986; Ashby and Rayner, 2004; Jones et al., 2008; Logan, 2009; Hawelka et al., 2010; Jones et al., 2010; Moll and Jones, 2013; Pan et al., 2013; Yan et al., 2013; Al Dahhan et al., 2014, 2017; Kuperman et al., 2016; Henry et al., 2018). Such differences in gaze patterns have been interpreted to reflect that those with reading difficulties require more attentional resources and time to attend and engage cognitive mechanisms in order to process information during fixations than normal age-matched readers. However, while many now argue that eye movements can be used to investigate the cognitive processes involved in RAN and reading (Al Dahhan et al., 2016; Eckstein et al., 2017; Kim et al., 2019), there is only limited research specifically exploring how well RAN eye movements predict RAN performance or reading outcomes. Establishing this would aid in confirming that using eye movements to study cognitive processing during RAN is useful in understanding the RAN-reading relationship.

Currently, we are only aware of two studies by Al Dahhan et al. (2014), that have reported on the extent to which eye movements recorded during RAN may predict single word reading and RAN performance. Al Dahhan et al. (2014) found that FD and count recorded during RAN significantly predicted reading in adults, while Al Dahhan et al. (2016) demonstrated that FD during rapid naming, predicted reading and RAN performance in children (aged 6–7 and 9–10) and concluded that RAN and reading are related *via* eye movements which reflect the time required to extract and process stimulus information. While the aims of both articles were to investigate the predominant theories of RAN *via* visual and phonological manipulation of RAN tasks, rather than investigate the role of eye movements, these previous results provide impetus for further investigations to establish such a role for text reading (Araújo et al., 2015; Papadopoulos et al., 2016) rather than single-word reading as used by Al Dahhan et al. (2014, 2017). The close relationship known between RAN and oral text reading is presumably because both skills draw on similar cognitive processes of visual stimulus identification and rapid sequential processing (Araújo et al., 2015; Papadopoulos et al., 2016)—skills less required for single word reading lists. This would suggest that RAN-based eye movements are likely to be more predictive of text reading skills as compared with single-word reading, necessitating the current study.

Thus, in the current study, we aimed to extend upon the works of Al Dahhan et al. (2014, 2017) to further clarify two aspects regarding the role of eye movements during RAN as a way to measure the RAN-reading cognitive "microcosm." A serial alphabetic RAN task was chosen because this type of RAN task most strongly predicts single reading across development (van den Bos et al., 2002). The first aim was the role of eye movements during a serial alphabetic RAN task and their relationship to RAN and oral text reading performance. We investigated this in a broad sample of primary school-aged learner readers by:

1. examining how well eye movements recorded during RAN predict RAN performance;
2. examining the extent with which eye movements and phonological awareness separately predicted RAN, to demonstrate whether RAN is more reflective of phonological processes or the cognitive "microcosm" eye movements are believed to reflect;
3. determining the unique contribution of RAN-based eye movements in predicting text reading accuracy, rate and comprehension performances and;
4. identifying the shared contributions between RAN and RAN-based eye movements as overlapping predictors of text reading performances, in order to further establish that eye movements can be utilized as proxy measures of RAN and as a means of identifying the microcosm of cognitive processes that underlie RAN and the RAN-reading relationship.

The second focus was on discriminating reading difficulties using eye movements, and in this aspect of the research we aimed to:

5. identify whether eye movements during RAN discriminate children with reading difficulties from chronological- and reading-age matched normal readers, which would further indicate that eye movement are useful measures of the cognitive processing underpinning reading development.

Based on the findings of previous research, we hypothesized that eye movement patterns during RAN would prove highly reflective of RAN performance, so would strongly predict RAN performance, and to a greater extent than phonological awareness. It was also hypothesized that eye movements during RAN would significantly predict text reading performances (accuracy, comprehension, and rate) more strongly than for the single words as used by Al Dahhan et al. (2014, 2017) and that the predictive contribution of RAN eye movements on text reading would largely overlap with the contribution provided by RAN performance. It was also hypothesized that eye movements would successfully differentiate children with reading difficulties from chronological-, and reading-age matched normal readers, providing further evidence that individual differences in eye movements are related to both RAN performance and the cognitive processes involved.

MATERIALS AND METHODS

Participants

For the first part of the study, ninety-three primary school children (52 male) aged 5 years to 9 years 2 months (mean age = 7.00, SD = 0.99), from Prep (i.e., the first year of formal schooling; n = 32), Grade 1 (n = 35), and Grade 2 (n = 26) participated in the study. Participants were tested towards the end of the school year to ensure that children in Prep had received close to 1 year of formal instruction of word and sentence reading. Participants were recruited from mainstream primary schools and an extracurricular program for children with diagnosed specific reading disorders to ensure the sample was representative of the full reading spectrum. All participants had normal intelligence (Standard score ≥85 for age), normal or corrected-to-normal vision and hearing, and English as their primary language. The sample included 23 participants diagnosed with specific reading difficulties (i.e., specific learning disorder in reading and/or developmental dyslexia), which was confirmed *via* standardized assessment (Reading performance >1.5 SD below age norms; O'Brien et al., 2012; American Psychiatric Association, 2013). Children with known medical and neurodevelopmental disorders other than developmental dyslexia or specific reading disorder were excluded (see DSM-5; American Psychiatric Association, 2013). **Table 1** provides descriptive statistics for all measures of interest.

TABLE 1 | Participants means and standard deviations for reading related measures and eye movements.

	M	*SD*	Min.	Max.
RCPM	115.96	9.45	91.00	125.00
Phonological awareness	104.16	15.27	70.00	145.00
RAN (raw score)	72.77	20.79	19.00	113.00
Reading accuracy	99.46	18.10	65.00	135.00
Reading comprehension	94.99	16.55	65.00	131.00
Reading rate	103.75	19.70	65.00	145.00
Fixation duration (ms)	442.37	71.50	270.22	510.00
Fixation count	1.71	0.35	1.13	2.52
Saccade duration (ms)	54.64	21.49	20.03	100.00

Note. Reading, phonological awareness, and RCPM means and SD's represent standard scores. ms, milliseconds; RCPM, Ravens Color Progressive Matrices.

For the second part of the study, a sub-sample of the recruited participants (n = 54) were further investigated in order to compare the eye movement patterns of those with and without reading difficulties. Children with reading difficulties (RD; aged 7–9; n = 18) were compared to chronological-age-matched controls (CA; aged 7–9; n = 18) and reading-age-matched controls (RA; aged 5–6; n = 18). RD children were one-to-one matched with both control counterparts (CA and RA) on age-standardized nonverbal intelligence (z = ± 0.8), with CA children within 1 year of age, and with RA children within 1 year of reading age. An *a priori* power analysis indicated that this sample size was sufficient to detect a large effect size with 95% power.

Procedure

The research was carried out in accordance with ethics approval granted by the La Trobe University Faculty Human Ethics Committee and the Victorian State Department of Education. Parents of participants were required to provide written informed consent for their child to engage in the study. All children voluntarily participated. Testing occurred in a small quiet room, over approximately two 30-min sessions at the participants' school or program, with tasks administered in randomized order.

Materials

Nonverbal Intellect

The Raven's Colored Progressive Matrices (RCPM) test was used to assess nonverbal reasoning (Raven et al., 1998). The RCPM contains three series of 12 matrices of increasing complexity. Standard scores were calculated based on chronological age using normative data provided in Cotton et al. (2005). The RCPM is standardized in a range of countries including Australia and is considered appropriate for children of ages 5–11 years and for children with reading difficulties (Cotton et al., 2005). The Raven's exhibits good test-retest reliability (r = 0.80; Raven et al., 1998) and high internal consistency (α = 0.89), with minimal variation across age (Cotton et al., 2005).

Reading Ability

Reading was measured with the Neale Analysis of Reading Ability—Third Edition, which is a standardized test of reading ability for children in Grades Prep to 6, commonly used in Australian school settings (Neale, 1999). The test measures reading accuracy, comprehension, and rate during prose oral reading *via* a series of up to six passages of increasing difficulty with accompanying questions. Children were first required to complete a practice passage, and all children were able to participate in the test. Grade-based standard scores for reading accuracy, comprehension and rate were calculated from the raw scores based on the manuals' normative data. Internal consistency results vary by age, with α ranging from 0.86 to 0.92 for comprehension, 0.91–0.97 for accuracy and 0.71–0.94 for rate (Neale, 1999). The overall measure has high content validity and face validity for the construct of reading aloud and is effective in discriminating between ages and differing reading abilities, including poor reading and dyslexia.

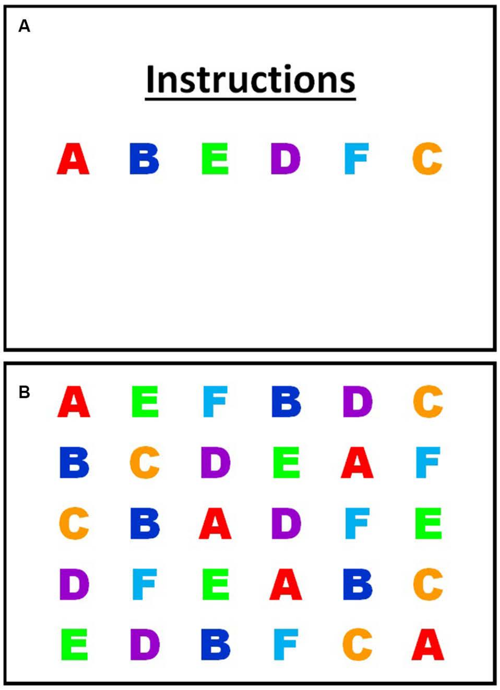

FIGURE 1 | Rapid Automatic Naming (RAN) practice trial **(A)**; RAN timed trial **(B)**.

Phonological Awareness

Phonological knowledge was assessed using the Elision subtest, a sound deletion task, from the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999). The age-based standard score was used as the measure of phonological awareness. It demonstrates good internal consistency (α =.91), test-retest (α = 0.82), and inter-rater reliability (r = 0.96), and has high concurrent validity with other tests of phonological processing (Wagner et al., 1999).

Rapid Automatized Naming

The custom serial letter RAN task employed here consisted of 30 items of six randomly repeated letters (see **Figure 1**). RAN performance was recorded as a number of stimuli named in 60 s, rather than time to complete, as used in most other RAN tasks. A performance indicator of RAN that controlled for the time was chosen as most of the eye movement variables included were time-based, while the 60 s time duration was selected to ensure that the averaged eye movement variables were representative. RAN tasks require stimuli to be named in a quick, automatic manner, so the uppercase letters A through F were chosen as stimuli because uppercase letters and letters from the beginning of the alphabet are learned earliest (McBride-Chang, 1999; Justice et al., 2006), so would be automatized earliest. Consistent with other alphabetic RAN tasks, each of the chosen stimuli were single-syllable. The task was presented as a single frame on a computer screen, and participants sat at a viewing distance of 60 cm. The visual angle of each letter was $2 \times 2°$. Participants were first provided a practice trial showing all six-letter stimuli to ensure they could name each letter without error and to familiarize them with the requirements of the task. Participants unable to accurately complete the practice trial were discontinued from the task. Participants were instructed to name aloud the stimuli as fast and as accurately as possible, from left to right, top to bottom, and repeating through the 30 stimuli as many times as possible, and self-correcting any errors, until the display disappeared (60 s). The total number of stimuli named was recorded manually. Eye-tracking data was then analyzed for the duration (60 s) of the task. Eye movements during naming errors were not removed from the data.

Eye Movement Patterns

Eye movements were recorded binocularly during the RAN task using a Gazepoint GP3 screen mounted infrared camera (60 Hz sampling rate; Gazepoint[1]). The GP3 tracks vertical and horizontal eye positions with an average gaze position accuracy of 0.5°. Participants were positioned 60 cm from the screen with their head placed in a chin and forehead

[1] www.gazept.com

TABLE 2 | Correlations between rapid naming, reading, phonological awareness, nonverbal intelligence, and eye movement patterns.

	2.	3.	4.	5.	6.	7.	8.	9.
1. RCPM	0.311**	0.448**	0.321**	0.335**	0.235*	−0.285**	−0.250*	−0.001
2. Rapid naming	-	0.377**	0.642**	0.600**	0.613**	−0.682**	−0.874**	−0.102
3. Phon. awareness	-	-	0.587**	0.497**	0.428**	−0.307**	−0.286**	−0.065
4. Reading accuracy	-	-	-	0.831**	0.823**	−0.437**	−0.540**	−0.065
5. Reading comp.	-	-	-	-	0.729**	−0.423**	−0.494**	−0.101
6. Reading rate	-	-	-	-	-	−0.502**	−0.486**	−0.019
7. Fixation duration	-	-	-	-	-	-	0.347**	−0.272**
8. Fixation count	-	-	-	-	-	-	-	0.098
9. Saccade duration	-	-	-	-	-	-	-	-

*Note. *p ≤ 0.05, **p ≤ 0.01. RCPM, Ravens Color Progressive Matrices; Phon. Awareness, phonological awareness.*

rest to reduce movement. Before beginning the task, each participant underwent a 9-point eye movement calibration procedure. FD was calculated as the average (mean) temporal length the fixations performed during the 60 s RAN task. Saccade Duration (ScD) was calculated as the average (mean) duration (in milliseconds) of saccades performed during the 60 s RAN task. This variable was chosen as it provides a summary measure of saccadic function (i.e., reflective of the speed of activation and time required to move the eyes to the next fixation location) that permitted investigation of eye movements more broadly while minimizing the number of variables included in analyses. FC was defined at the average number of fixations required per stimuli named and was calculated by dividing the total number of fixations made by the total number of letters named during the RAN task. As the RAN task used a fixed time limit rather than number of stimuli, the FC variable controls for individual participant RAN score differences (i.e., differences in the number of letters named), and so is akin to FC measures used in experiments presenting a fixed number of stimuli.

DATA SCREENING AND ANALYSIS

Data screening identified a total of 12 outliers across the eye movement measures (FD = 3; ScD = 6; FC = 3) that were just outside the normal distribution (i.e., ∼4% of the eye movement data). To reduce this influence on parametric statistical analyses, outliers were pulled back to the next most extreme value within the normal distribution (Tabachnick and Fidell, 2013). Further assumption testing revealed no other violations.

Correlation analyses were conducted to determine which, if any, eye movement measures related to RAN and to inform which to include in the regressions. High correlations between the eye movements variables and RAN performance were found, suggestive of non-independence between the variables. This was not unexpected as the eye movements were recorded during the RAN task. Although multicollinearity between predictor variables is typically addressed by removal of one of those variables from the regression model, this was not performed in the current study given that multicollinearity has been shown to not reduce the reliability or predictive power of the regression model, rather only reducing the likelihood that individual predictors will be statistically significant (Allen, 2004). Therefore, a series of hierarchical multiple regressions were conducted to investigate what contribution eye movement patterns may make to RAN and to text reading ability (i.e., accuracy, comprehension, and rate) in young readers. The regression analysis for RAN included phonological awareness and the chosen eye movement variables to allow direct comparison of their contributions, and to identify whether RAN is more reflective of phonological processes or the cognitive "microcosm" eye movements are believed to reflect. In each regression model for text reading (accuracy, rate, comprehension), the aim was to determine the unique contribution that eye movements provide to the reading skills, as well as the overlap in the contribution of eye movements and RAN, to reading. Other variables that are known to be important to reading, such as phonological awareness, were not included in the reading regressions as this has been previously investigated (see Al Dahhan et al., 2014). Eye movements were entered at step 1 to determine specifically what unique contribution they made independent of the broader RAN performance variable. RAN performances were then entered at step 2 to determine what further contribution RAN made to the reading models and how much variance contributed by eye movements and RAN was shared.

For the second part of our research, reading subgroups were compared using one-way analysis of variance (ANOVA's) to ascertain whether eye movements could differentiate between a group of children with reading difficulties, a matched group of chronological-aged normal readers, and a group matched on reading-age.

RESULTS

The Relation of Eye Movements to Rapid Naming Performance and Reading

Pearson correlational results show that FD and FC correlated significantly with nonverbal intelligence, RAN, phonological awareness and all reading measures (see **Table 2**). Saccade duration did not correlate with these measures.

Predictors of Rapid Naming

The independent eye movement variables, FC and FD, were chosen for the hierarchical multiple regression for RAN performance based on the significant correlations shown in **Table 2**. Phonological awareness was included based on past theoretical considerations of its importance to RAN. Therefore,

TABLE 3 | Predictive contributions of phonological awareness and eye movement patterns on alphabetic rapid naming performance.

Alphabetic rapid naming performance	β	r	sr
Phonological awareness	0.04	0.38	−0.04
Fixation duration	−0.42**	−0.68	−0.38
Fixation count	−0.72**	−0.87	−0.66
Total $R^2 = 0.928$, $F_{(3,84)} = 362.293$, $p < 0.001$			

*Note. **p ≤ 0.001; according to Cohen's guidelines, r ≥ 0.10, r ≥ 0.30, and r ≥ 0.50, represent small, medium, and large effect sizes, respectively (Cohen, 1988).*

phonological awareness, FD and FC were entered together as predictors of letter RAN performance.

The results in **Table 3** show that only the two eye movement measures (FD and FC), and not phonological awareness, were significant predictors of RAN performance, together explaining 92.8% of the variance in the regression model. These results indicate that eye movements—namely shorter and fewer fixations made for each stimulus named—are highly predictive of the rate of rapid naming performance in young readers, with more efficient eye movements relating to better performance outcomes and so should be considered as discrete substitute measures of RAN.

Predictors of Reading Ability

Hierarchical multiple regressions were conducted for each text reading skill, despite the dependent variables (reading accuracy, comprehension, and rate) being highly correlated (see **Table 2**), because the contributions of RAN-based eye movements to each of the three aspects of text reading is not fully known. For each analysis, FD and FC were entered as predictors at Step 1 to first establish the contribution of these discrete functions given their overlap with RAN as shown in the previous analyses, with RAN performance then entered at Step 2 to determine how much more variance it may contribute to the text reading analyses. Assumption testing revealed no violations. **Table 4** presents the results of each reading regression (reading accuracy, comprehension, and rate) respectively.

The total variance explained by the reading accuracy regression model was 41.5%. FD and FC explained 36.3% of the variance at step 1, with RAN then explaining an additional 5.2% at step 2. The total reading comprehension analysis explained 36.5% of the variance. FD and FC together explained 31.6% of the variance at step 1, and when entered at step 2, RAN performance explained an extra 4.9% of the variance. The total reading rate regression model explained 39.0% of the variance. At step 1, the two eye movement measures explained 36.2% of the variance, while RAN performance explained an extra 2.8% of the variance in step 2, although this was not a significant contribution.

However, when independent variables were considered separately the significance of eye movement measures no longer remained in any of the three final regression models. This is most likely due to the high level of overlap between RAN and the eye movement measures, as shown in the previous correlation and RAN regression analyses. In the final regression analyses for text reading, RAN was the only significant and individual predictor for Reading Accuracy and Comprehension, while no variable remained a significant unique predictor for Reading Rate.

Reading and Age Comparisons Between Those With and Without Reading Difficulties

Results of initial group comparisons confirmed that the three groups were appropriately comparable. Preliminary analyses revealed no assumption violations. Raw scores for reading were used to facilitate comparisons during analyses; however standard scores and age-equivalents for reading have been provided in **Table 5** to aid meaningful interpretation. Groups did not differ on age-standardized nonverbal intelligence (i.e., Raven's; $F_{(2,50)} = 0.42$, $p = 0.659$, $d = 0.25$). The RD and CA groups did not differ in chronological age ($F_{(2,50)} = 44.05$, $p > 0.001$, $d = 2.65$; Tukey HSD *post hoc* comparisons showed only the RA group differed significantly from the RD and CA groups), while the RD and RA groups did not differ on reading age or phonological awareness, with only the CA group performing significantly better than the RD and RA groups (Reading accuracy, $F_{(2,50)} = 30.35$, $p < 0.001$, $d = 2.20$; comprehension, $F_{(2,50)} = 28.23$, $p < 0.001$; $d = 2.24$; rate, $F_{(2,50)} = 21.66$, $p < 0.001$, $d = 2.01$), and phonological awareness, $F_{(2,50)} = 6.45$, $p = 0.003$, $d = 1.06$). Statistically significant differences between groups for RAN performance were also found ($F_{(2,50)} = 8.08$, $p = 0.001$, $d = 1.14$), with the CA group performing better than the RD group.

Comparisons of Eye Movements During Rapid Naming in Children With and Without Reading Difficulties

One-way ANOVA comparisons of the eye movement patterns of children with reading difficulties, chronological-age matched controls and reading-age matched controls demonstrated statistically significant differences between groups for FD ($F_{(2,50)} = 3.90$, $p = 0.027$, $d = 0.80$) and FC ($F_{(2,50)} = 4.66$, $p = 0.014$, $d = 0.87$), with large effect sizes found. There were no differences between groups for ScD ($F_{(2,50)} = 2.45$, $p = 0.097$, $d = 0.63$). *Post hoc* comparisons using the Tukey HSD test indicated that the CA group differed significantly from the RD group in FD (414.30 vs. 472.45 ms) and FC (1.55 vs. 1.89 fixations), with chronological-age-matched controls making more fixations on the RAN task with shorter average duration of fixations and fewer fixations per stimulus than those with reading difficulties. Neither group differed significantly from the reading-age-matched controls in FD (465.94 ms) or FC (1.73 fixations). **Figure 2** depicts the performance of each reading group for the Fixation Count (FC; **Figure 2A**), Fixation Duration (FD; **Figure 2B**), and Saccade Duration (ScD; **Figure 2C**).

DISCUSSION

The current study examined eye movement patterns during rapid naming in young children to better elucidate the extent to which the temporal constraints in eye movements and attention shifting predict and can, therefore, be considered reflective of RAN performance. We are assuming that if eye movements during RAN explain significant variance in RAN performance, this should establish that eye movements can be used to operationalize and temporally sequence the microcosm of

TABLE 4 | Predictive contributions of eye movement patterns and RAN on reading accuracy, reading comprehension, and reading rate.

		Reading accuracy			Reading comprehension			Reading rate		
		β	*r*	*sr*	*β*	*r*	*sr*	*β*	*r*	*sr*
Step 1:	Fixation duration	−0.28*	−0.44	−0.27	−0.29*	−0.42	−0.19	−0.38**	−0.50	−0.36
	Fixation count	−0.44**	−0.54	−0.41	−0.40**	−0.49	−0.30	−0.35**	−0.49	−0.33
		R^2 = 0.363**, *F* change (2,89) = 25.34			R^2 = 0.316**, *F* change (2,89) = 20.59			R^2 = 0.362**, *F* change (2,859) = 24.12		
Step 2:	Fixation duration	0.08	−0.44	0.04	0.07	−0.42	0.03	−0.12	−0.50	−0.06
	Fixation count	0.17	−0.54	0.06	0.20	−0.49	0.07	0.09	−0.49	0.03
	Rapid letter Naming	0.84*	0.64	0.23	0.82*	0.60	0.22	0.61	0.61	0.17
		Change R^2 = 0.052*, *F* change (1,88) = 7.87			Change R^2 = 0.049*, *F* change (1,88) = 6.79			Change R^2 = 0.028, *F* change (1,88) = 3.79		
		Total R^2 = 0.415**, $F_{(3,88)}$ = 20.82			Total R^2 = 0.365**, $F_{(3,88)}$ = 16.88			Total R^2 = 0.390**, $F_{(3,88)}$ = 17.87		

Note. **p* ≤ *0.05,* ***p* ≤ *0.001; according to Cohen's guidelines, r* ≥ *0.10, r* ≥ *0.30, and r* ≥ *0.50, represent small, medium, and large effect sizes, respectively (Cohen, 1988).*

TABLE 5 | Participants means and standard deviations for age, nonverbal intelligence, and reading related measures.

	Reading disorder group (*n* =18)		Chronological-age-matched control group (*n* =18)		Reading-age-matched control group (*n* =18)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Age in years	7.71	0.78	7.65	0.63	5.91	0.50
RCPM SS	107.72	10.13	110.52	6.88	109.11	9.71
RAN (raw score)	59.89	17.12	84.47	19.88	70.72	17.28
Phon. awareness SS	87.35	7.09	107.00	14.24	102.35	11.06
Phon. awareness age equiv	6.36	0.70	9.18	2.80	6.28	0.87
Reading accuracy SS	75.00	8.08	110.35	12.16	102.44	6.50
Reading accuracy age equiv	6.21	0.41	8.57	2.12	6.37	0.35
Reading comprehension SS	77.55	11.71	101.00	13.63	94.89	11.81
Reading comprehension age equiv	6.30	0.54	7.62	0.97	6.25	0.37
Reading rate SS	80.83	13.66	118.07	15.15	104.88	12.45
Reading rate age-equiv	6.63	1.13	10.00	2.38	6.72	0.87

Note. SS, Standard score; RCPM, Ravens Color Progressive Matrices; Phon. Awareness, phonological awareness; Age Equiv, age equivalent score.

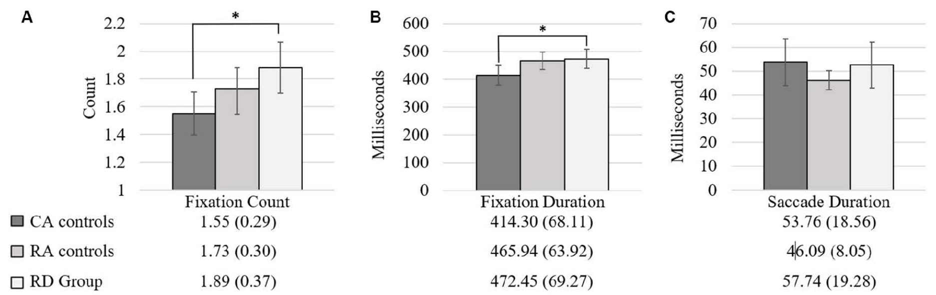

FIGURE 2 | Group differences for fixation count (FC; **A**); fixation duration (FD; Milliseconds; **B**); and saccade duration (Milliseconds; **C**). *Note.* *$p \leq 0.05$; 95% Confidence interval error bars.

attentional and higher cognitive processes required for successful object recognition and verbalization as in RAN. Such knowledge also facilitates understanding of the relationship between RAN and oral text reading. The results provide evidence in support of the notion that RAN and text reading ability (accuracy, rate and comprehension) can be significantly predicted by the efficiency of eye movement behavior during RAN in 5-8-year-old children and that these eye movements also successfully differentiate age-matched children with and without reading difficulties. Moreover, our findings indicate that the average FD and FC per RAN item named is highly predictive of RAN, and that these eye movements and RAN show a strong overlap in their predictive contributions to text reading, suggesting that eye movements recorded during RAN reflect much of the cognitive processing required by both RAN and reading. Our interpretation of these measures is based on research (Eckstein et al., 2017; Kim et al., 2019) demonstrating that individual differences in temporally-based *fixation durations* are indicative of the duration of attentional engagement related to the speed of visual, symbolic, and orthographic processing. By comparison, average *FCs* per stimuli provide a measure of the spatial distribution of attention indicative of the amount of visual information processed in each fixation.

What Predicts Rapid Naming?

Duration and count of fixations (FD and FC) were recorded during RAN and were found to contribute significantly to RAN performance (92.3%), raising the question of variable independence. Eye movement variables have been interpreted as highly reflective of overall RAN performance rather than as independent, individual predictors. Since our results indicated that eye movements did not entirely account for RAN performance, additional factors must contribute to RAN performance. Our results are consistent with those reported by Al Dahhan et al. (2016), who found that FD, saccade count and number of regressions accounted for 83% of the variance in rapid naming. Indeed our findings also reiterate meta-analytical evidence (Swanson et al., 2003) showing that while phonological awareness and RAN correlate, they load to separate factors of reading indicative of an inadequate explanation for rapid naming ability and suggestive that FD times are not solely mediated by the time needed for phonological activation and retrieval at each fixation. Other evidence against a phonological interpretation comes from Compton (2003) who showed that increasing the visual (orthographic) similarity of the letters within a RAN task negatively affected performance to a much greater extent than increasing phonological similarity. Furthermore, Georgiou et al. (2013) showed that while rapid discrete naming of stimuli (presented one-at-a-time) has similar phonological processing requirements to rapid serial naming of multiple stimuli (presented in an array), it is less well correlated to reading. The relationship between RAN and reading also increased considerably when the "naming" aspect of RAN was accounted for by controlling the effect of discrete RAN on serial RAN performance, suggesting that speed of lexical access does not significantly mediate the RAN-reading relationship (Logan et al., 2011). Consistent with this research, our findings show that eye movement patterns, specifically the amount of time needed to acquire information (FD) and how much information is processed at each fixation (FC), are the most important factors in predicting RAN performance, suggesting that it is not phonological skills that are important for RAN ability, but rather the broader cognitive and attentional process (i.e., the "microcosm") that eye movements incorporate.

What Predicts Text Reading Skills?

Duration and count of fixations (FD and FC) each made significant contributions to reading accuracy, comprehension, and rate in young readers—together accounting for 36.3%, 31.6%, and 36.2% of the variance respectively. This is higher than the findings of Al Dahhan et al. (2016), who found that eye movement during RAN only accounted for 15% of the variance in word reading skill. We argue that the larger predictive power of RAN-based eye movements in the current study is likely to reflect the use of a text reading measure, rather than word lists, as gaze patterns during RAN would be a closer approximation of the eye movements required in oral text reading.

Entering the eye-movement components into the text reading regressions before RAN, enabled investigation of the unique contributions of eye movements to reading as well as further assessment of the RAN-reading relationship. As expected, once FD and FC had been accounted for, RAN only contributed a further 5.2% of variance to reading accuracy, 4.9% to comprehension and no further significant variance to reading rate. This highlights not only an important overlap of contribution between RAN and the fixation variables to text reading ability but also a small but important contribution of RAN to text reading independent of the variance explained by eye movements. When all predictors were compared once RAN was added to the regression analyses, FD and FC were unsurprisingly no longer significant unique predictors for reading accuracy, comprehension or rate, with RAN becoming the strongest predictor. Thus, the amount of time needed to acquire information (FD) and the number of fixations needed to acquire this information (FC) is closely related to individual differences in reading performance, suggesting that proficiency in fixation behavior can play a role in elucidating much of the relationship between RAN and reading.

Do Eye Movements Differentiate Children With and Without Reading Difficulties?

Children with reading difficulties were shown to have less proficient fixation characteristics than chronological-age matched controls, with proficiency being measured as the average length of FD and number of fixations (1.89 vs. 1.55 fixations) needed for successful naming of each RAN stimuli. Interestingly, neither of these groups showed eye movement differences when compared to a younger control group (1.73 fixations) who were matched on reading-age to those with reading difficulties. No difference in saccade duration was found between groups. The results are comparable with other eye-tracking studies of RAN (Yan et al., 2013; Al Dahhan et al., 2016). Children with reading difficulties (aged 9–10 years) have been shown to perform significantly worse than age-matched controls for RAN task efficiency errors, FDs, regressive fixations, articulation times, and pause times (Al Dahhan et al., 2016). Similarly, Yan et al. (2013) reported that 10-year-old Chinese children with reading difficulties process less parafoveal information, requiring more attention for local (foveal) processing of individual letters than controls, inevitably inhibiting their ability to anticipate the next character/icon and hence the rate of rapid naming. This would also result in requiring more fixations per stimuli. It appears that those with reading difficulties are generally less efficient than aged-matched normal readers in their eye movement driven temporal processing of information on RAN tasks, despite being familiar with the stimuli; and therefore, apparently requiring more attention and longer fixations for the required cognitive processes.

The less mature eye movement patterns seen in those with reading difficulties may also result from spatial and temporal sequencing deficits associated with impaired magnocellular processing and neural timing (Stein, 2003). It has been suggested that deficient magnocellular neurons are likely to reduce attentional focus, preventing the linked parvocellular neurons from isolating and sequentially processing the relevant information, and resulting in the diffused attentional distribution experienced by those with a reading disorder (Geiger et al., 1994; Facoetti et al., 2000; Lorusso et al., 2004; Lawton, 2007; Laycock and Crewther, 2008; Laycock et al., 2012). This would lead to reduced efficiency in cognitively extracting information during fixations, leading to more fixations, longer fixations and more regressions (Stein, 2003), and highlights the increasing importance of investigating eye movement patterns in both reading research and clinical settings.

Limitations and Future Directions

The statistical limitation of using a continuous variable (Reading Accuracy on the Neale) to determine group membership in the sub-sample comparison analyses is an important one but was performed with the sound rationale of comparing clinical and neurotypical populations to further inform understanding of reading difficulties (Cohen, 1988). It is also acknowledged that the use of a FC variable partially based on RAN performance (average number of fixations per stimuli named) may pose a statistical limitation influencing the results of the RAN regression. This is of particular importance for samples of more proficient readers who may make a single fixation per stimuli, as this would lead to FC becoming the inverse of the number of RAN stimuli named. However, the current study of emerging readers included children with reading difficulties through to fluent readers, and as such there was a range of variability in FC (i.e., 1.13–2.52 fixations per stimuli; see **Table 1**) within the sample. It will be important for future research to carefully consider the influence of interdependency of eye movements variables with measures of the task in which they are recorded. What also remains to be further investigated is the influence of the underlying cognitive processes on eye movement patterns and how these processes link to individual eye movement variables during RAN. For instance, there is already some evidence to suggest that the average duration of fixation may reflect the efficiency of visual/orthographic acquisition from the target stimulus (Al-Wabil and Al-Sheaha, 2010; Bellocchi et al., 2013; Al Dahhan et al., 2017). RAN itself also clearly involves well-directed visuo-attention and processing, as well as the speed of orthographic, phonological and semantic identification, and ability to inhibit previously named stimuli, sequentially update, and monitor ensuing information (Executive function; see O'Brien et al., 2012; Al Dahhan et al., 2016). Deficits have been found in those with reading difficulties in each of these aforementioned areas (Ramus et al., 2003; Reid et al., 2007; Menghini et al., 2010). Finally, while the current study does not address the mechanistic link of eye movements and reading, there are already a number of reading intervention studies that target eye movements (see reviews by Bucci, 2019; Peters et al., 2019).

CONCLUSION

In summary, the findings of the current study add to the body of evidence supporting the notion that eye movements can be used as surrogate measures to investigate many of the cognitive and attentional processes that underpin the relationship between RAN and reading. While those advocating that RAN and the RAN-reading relationship are predominantly reflective of phonological processes continue to be cited (Wagner et al., 1994; Torgesen et al., 1997; Clarke et al., 2005; Vukovic and Siegel, 2006; Savage et al., 2007; Ziegler et al., 2010), our results add to the literature supporting an alternative explanation (Compton, 2003; Thomson et al., 2006; Powell et al., 2007; Jones et al., 2008; Al Dahhan et al., 2014). Rather, RAN and reading is more likely related by the ability to rapidly process multiple visual stimuli *via* a cognitive "microcosm," as originally proposed by Denckla (1988). As such behavior can be measured by fixation behavior during RAN, eye movement patterns demonstrated during RAN should provide a way to further elucidate the RAN-reading relationship. Further research into how eye movement measurements can provide real-time insight into the cognitive processes underlying RAN and reading, including mapping cognitive processes to specific eye movements, is the next step in understanding the association between RAN and reading.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Ethics approval for the current research was given by La Trobe University Human Ethics Committee and the Victorian Department of Education and Training. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

JP, EB, and SC contributed to the conception and design of the study. JP collected the data, performed the statistical analysis and wrote the first draft of the manuscript. All authors contributed to manuscript revision, and read and approved the submitted version.

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